The Impact of Light Including Non-Image Forming Effects on Visual Comfort

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To the memory of my grandmother.

Abstract

Visual comfort at workplaces has often been considered in terms of discomfort glare, luminance distribution and task visibility. Besides visual effects, the lighting environment has also impact on human physiology and behaviour. These effects of light are transmitted via a novel class of photoreceptors in the mammalian retina, which was discovered only a decade ago. Since then, it has become evident that light also plays an important role in regulating Non-Image Forming (NIF) functions such as circadian rhythms, alertness, well-being and mood. In lighting design it is accordingly necessary to take into account not only luminous intensity, but also light's spectral composition, since the novel class of photoreceptors is more maximally sensitive to different luminous wavelengths than the classical photoreceptors (e.g. rods and cones).

The main focus of this doctoral thesis is on visual comfort assessment at workplaces. It was hypothesized that the impact of light on visual comfort comprises not only luminance distribution and/or luminous intensity, but also other qualitative aspects of the lighting environment. Office lighting influences building occupants in terms of visual task performance, alertness, health and well-being. The aim of this thesis was to assess the impact of office lighting on visual comfort including NIF effects.

Firstly, in order to monitor the luminance distribution within a scene, a new photometric device based on a high dynamic range logarithmic visual sensor (IcyCAM™) was set up. After calibrations and validations, the photometric device was used to assess luminance distribution of office spaces in a very efficient way. Secondly, two experimental studies were performed with human subjects, aiming to test the acute effects of light on visual comfort variables, subjective alertness, mood and well-being. Lastly, the novel device was also used during one of the studies to monitor the impacts of luminous distribution over time and under various lighting conditions.

The novel photometric device enables to assess luminous distribution also in circadian metrics with respect to NIF effects of light. The results from the two studies showed the effects of office lighting including different sky conditions and time-of-day changes on visual comfort and NIF functions. Inter-individual differences, as assessed in extreme chronotypes, also had an influence on visual comfort. Interestingly, luminance distribution was not only found to impact on visual comfort but also on subjective alertness, mood and well-being. To conclude, the results obtained with the new device provide a more comprehensive scientific framework and practical basis for indoor lighting design at workplaces.

Keywords: Lighting conditions, visual comfort, work environment, non-image forming effects, photometric measurement, circadian rhythms

Résumé

Le confort visuel dans le cadre professionnel a souvent été abordé en termes d'éblouissement, de distribution de luminance et de visibilité adaptée à la tâche effectuée. Au-delà des effets visuels, l'environnement lumineux a aussi un impact sur la physiologie et les comportements humains. Ces effets sont principalement régis par une nouvelle classe de photorécepteurs, situés sur la rétine des mammifères, découverte il y a une dizaine d'années. Depuis lors, l'importance du rôle de la lumière sur le rythme circadien, la vigilance, le bien-être et l'humeur a été démontrée. Ces effets, indépendants de la formation d'images ('Non-image Forming Effects' or 'NIF effects'), s'ajoutent aux effets visuels précédemment étudiés. Il est donc nécessaire de tenir compte non seulement de l'intensité lumineuse, mais également de la composition spectrale de la lumière lors de projets d'éclairage, puisque cette nouvelle classe de photorécepteurs est sensible à des longueurs d'onde différentes des photorécepteurs classiques, que sont les bâtonnets et les cônes.

Le thème principal de cette thèse est l'étude du confort visuel dans l'environnement de travail. Le postulat de base est que l'impact de la lumière sur le confort visuel dépend non seulement de la distribution et/ou de l'intensité lumineuse, mais aussi de la qualité des conditions d'éclairage. En outre, il est désormais évident que l'éclairage de bureaux affecte les performances visuelles, la vigilance, la santé et le bien-être des occupants. Le but de cette thèse est d'évaluer l'influence de l'éclairage de bureaux sur le confort visuel, en incluant les fonctions NIF. Dans une première étape, et afin de pouvoir mesurer la répartition des luminances au sein d'une scène visuelle, un luminancemètre digital basé sur un senseur lumineux à grande dynamique et à réponse logarithmique (IcyCAM™) a été mis sur pied. Deux études expérimentales ont ensuite été réalisées dans le but de tester les effets les plus significatifs de la lumière sur différents aspects subjectifs du confort visuel, le degré de vigilance, l'humeur et le bien-être au cours de la journée. Finalement, le nouveau capteur photométrique a été mis en œuvre au cours de ses études : les effets de la distribution lumineuse ont ainsi été mesurés au fil du temps sous plusieurs conditions d'éclairage.

L'utilisation du nouveau capteur a permis ainsi d'atteindre le but de cette thèse avec succès. En plus des mesures photométriques, celui-ci donne accès à la distribution de luminance dans une unité de mesure circadienne, qui tient compte des effets NIF de la lumière. Les résultats des deux études ont mis en évidence l'effet des conditions d'éclairage, de la couverture nuageuse et de l'heure sur le confort visuel et les fonctions NIF. Les différences entre individus, tels que les chronotypes extrêmes, ont aussi une influence sur le confort visuel. Par ailleurs, l'effet de la distribution lumineuse a été démontré, non seulement sur la dimension subjective du confort visuel, mais également sur la vigilance, l'humeur et le bien-être. Finalement, les résultats de cette thèse fournissent une base scientifique et pratique plus complète, en vue de la conception en éclairage dans le cadre de l'environnement de travail.

Mot-clés : éclairage, confort visuel, environnement de travail, impacts non-visuels, mesure photométrique, rythme circadien

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Glossary

General terms	
NIF	Non-Image Forming
ipRGC	intrinsically photosensitive Retinal Ganglion Cells
HDR	High Dynamic Range
CLLS	Camera-Like Light Sensor
f_1'	CIE deviation of the relative spectral response from the V(λ) function
Photometric variables	
E_v	Vertical illuminance (lx)
CCT	Correlated Colour Temperature (K)
CRI	Colour Rendering Index
E_{ec}	Circadian weighted irradiance (W/m^2)
L_{ec}	Circadian weighted radiance (W/sr·m^2)
Lighting conditions	
DL	Daylighting condition
EL	Electric lighting condition
DIM	Dim lighting conditions
BL	Bright lighting conditions
SSL	Self-selected conditions
Glare indices	
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
UGR	Unified Glare Index
Subjects	
ET	extreme Evening Types
MT	extreme Morning Types

Chapter 1 Introduction

1.1 The role of office lighting

The quality of the indoor environment within office buildings influences white-collar workers in their behaviour and with regard to organizational outcomes. An optimal indoor environment can improve comfort, productivity, health and well-being [1-3]. It was reported that workers' satisfaction with regard to their work environment induced greater job satisfaction and organization commitment as well as less absentees [4-7]. Environmental satisfaction derives from several factors; light is very important in this prospect: it represents the bulk of this thesis.

In the framework of a large interdisciplinary project dedicated to workers' satisfaction in open-plan office conditions [5, 8, 9], data were collected from 779 workstations within 9 buildings in Canada and US cities during two years (2000-2002). Physical variables at individual workstations, such as lighting, acoustic, thermal and air movement conditions were monitored for that purpose. The participants were requested to express their satisfaction regarding their work environment, as well as their overall job satisfaction by means of a survey. The statistical analysis of the survey indicated the existence of a clear link between environmental and job satisfaction (Figure 1.1). The overall environmental appraisal was affected by the workers' own satisfaction with the physical variables regarding ventilation, privacy, acoustics and lighting [5]. In a subset analysis, predictor variables related to satisfaction with lighting conditions were analysed on the basis of the monitored data. Five variables that specifically related to satisfaction with lighting were: i) preferred illuminance, ii) glare sensations from Video Display Terminal (VDT) iii), lighting uniformity, iv) light directionality (ratio of horizontal and vertical planes), as well as v) presence of a window. The most important variable was the last one: the fact of having a window next to the work space, or the fact of benefitting from daylight, significantly improved satisfaction of office workers with regard to lighting [8].

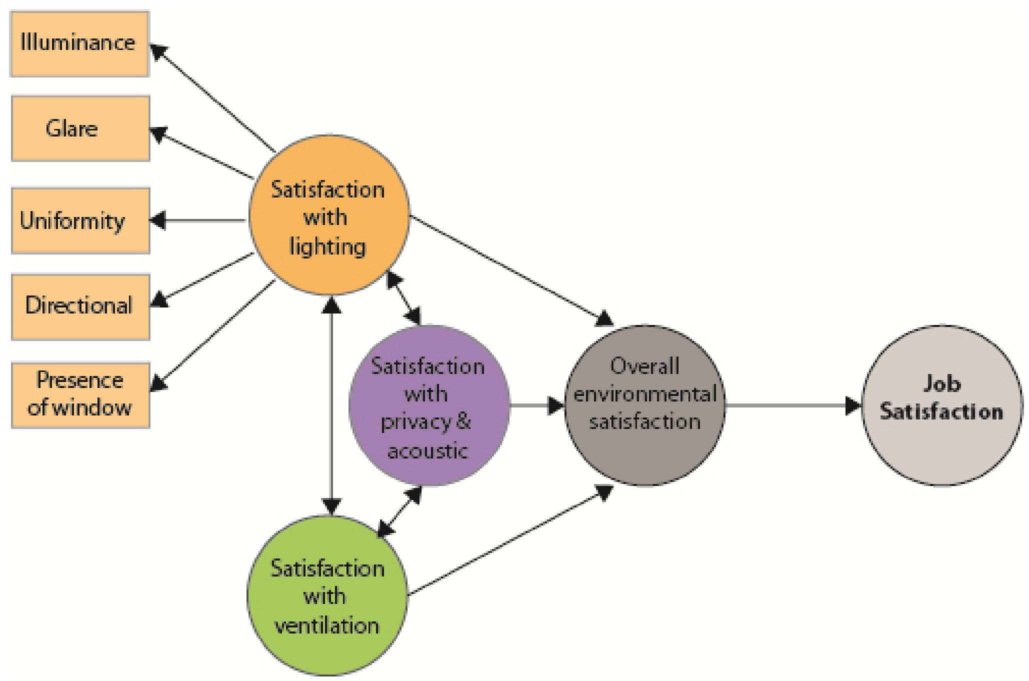

Figure 1.1: Conceptual model showing the relationships between the physical environment and job satisfaction, based on the data from questionnaires (modified from [5, 9]). The predictor variables for satisfaction with lighting are indicated on the left side (orange rectangles) (adapted from [8])

Interestingly, according to the study, lighting satisfaction does not only imply sufficient brightness for the sake of task visibility. The related physical factors also include visual comfort and the presence of windows. Figure 1.2 illustrates office environments benefitting from daylight as well as from the presence of windows.

a)

b)

Figure 1.2: Examples of office spaces with daylighting from windows; a) large open office at Lufthansa headquarters in Frankfurt airport, Germany [10]; photography by H.G. Esch; permission by "ingenhoven architects"; b) small office space at LESO Solar Experimental building (EPFL, Lausanne, Switzerland).

Different colours of light sources impact the atmosphere of a working space; day- and electric lighting can create different atmospheres of light. Figure 1.3 describes these different effects simulated by Karcher [10]. An office with different lighting systems is illustrated by simulations including: daylight from the window (Figure 1.3a), daylight and incandescent lamps (Figure 1.3b), daylight and fluorescent lamps with Correlated Colour Temperature (CCT) at 4000 K (Figure 1.3c), incandescent lamps only (Figure 1.3d) and fluorescent lamp with CCT at 4000 K only (Figure 1.3e). Our perceptual system is affected by different lighting conditions, such as light sources, colour temperature and luminous intensity; this influences our mood and behaviour. The effects of light have been further explored in order to understand how lighting impacts our daily life and what the other consequences are.

Figure 1.3: Various simulated effects of light created by different light sources: a) daylight from the window; b) daylight and incandescent lamps; c) daylight and fluorescent lamps with CCT at 4000K; d) incandescent lamps only; e) fluorescent lamps only. These images were simulated by Karcher for Electric Gobo, Berlin, Germany [10].
These have been given permission to be reproduced in this work by ERCO GmbH, www.erco.com.

A decade ago, a new class of photoreceptors in the retinal ganglion cells (the so-called intrinsically photosensitive Retinal Ganglion Cells; ipRGC) were discovered; they are mainly responsible for the non-visual light perception which regulates circadian functions, the pupil light reflex and hormonal secretions [11-15]. Since then, it has been demonstrated that besides visual effects of light (perceived by rods and cones), there are also non-visual biological effects: the so called "Non-Image Forming (NIF)" effects of light, which impact many circadian functions in humans, as well as alertness and well-being (see Chapter 4). Emotion is impacted by both, visual and NIF effects of light as illustrated in Figure 1.4 [16]. Visual effects of light affect visual performance; NIF effects of light impact health and well-being.

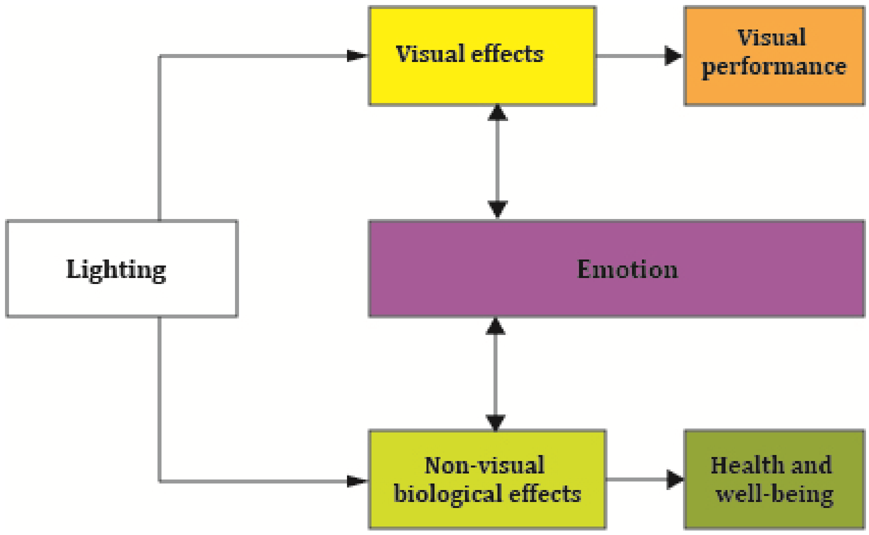

Figure 1.4: Conceptual relationships between lighting, visual and non-visual effects of light, as described by Van Bommel [16]

The groups of Boyce and Veitch performed two experiments with 188 participants to assess the impact of different (mainly artificial) lighting conditions on participants' behaviour with several questionnaires [17]. According to the results, Veitch et al suggested different links between lighting effects (the so-called "linked mechanisms map"), as illustrated in Figure 1.5 [18]. Their model included two paths: an appraisal path (light perception) and a visual path. Via the visual path, lighting conditions fostered the visibility leading to better task performance; this might reflect the "visual effects" of light. The appraisal path describing the influence of lighting conditions was related to health and well-being in terms of lighting preference and mood. The authors pointed out a positive correlation between lighting appraisal and visual comfort: a higher appraisal of lighting conditions was linked with a better visual comfort. Initially, the authors hypothesized that visual comfort was directly affected by lighting conditions, and also related to visual capabilities and task performance. However, they could not demonstrate that these links were statistically significant: they explained this by the fact that lighting quality in the study was rated high, while visual discomfort ratings were rated low [18].

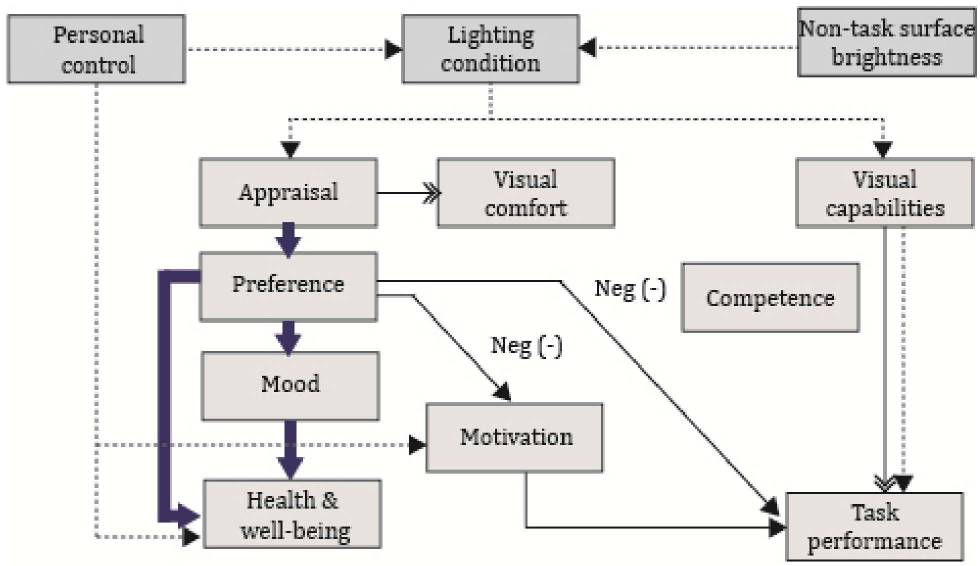

Figure 1.5: Links of visual and non-visual effects of lighting conditions. Solid lines show the results which were supported by mediated regression analysis (heavy blue lines show the appraisal path and double-headed arrows show the vision path); dotted lines show results which were supported by the statistical analysis (MANOVA and ANOVA); solid lines show weaker links supported by mediated regression results (according to [18]).

Visual comfort has been generally considered as a predictor of lighting quality, which includes visual comfort, satisfaction and performance, the so-called "CSP" index. This index was based on a survey of office workers' opinion regarding lighting quality [19, 20]. The authors suggested that the appraisal of a lighting environment depended on these three elements (Figure 1.6). Visual comfort has generally been considered to be fully independent from visual performance: lighting conditions favourable for visual performance might be uncomfortable. Visual comfort is a human-responsive factor linked to occupants' expectation which can change over time [21, 22]: this may imply that visual comfort could be linked both to visual and to NIF effects of light.

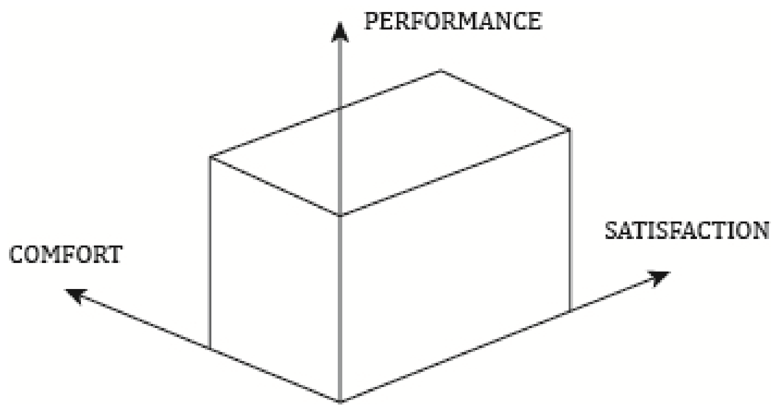

Figure 1.6: The three dimensions of visual comfort, satisfaction and performance, defining the ''CSP'' index according to [20]

1.2 Short summary and open questions

Satisfaction with lighting is related to job satisfaction, which contributes to organizational outcomes. Lighting conditions also have an influence on occupants' individual behaviour such as mood, well-being and task performances. Light induces both visual and non-visual biological effects; the link between these two opposed paths has so far remained unclear.

International standards and lighting recommendations for workspaces have existed for several decades. However, most defined criterions aimed solely at meeting visual requirements for related visual tasks. There are doubts whether or not the current lighting norms are also adequate for other human factors such as health and behaviour, leading to better work performance and organizational outcomes. To take into account the NIF effects of light, it is necessary to optimize lighting conditions in order to satisfy both visual and non-visual requirements. This might lead to both, better work performance and better health.

Visual comfort is the main topic of this doctoral thesis: it is assumed to be the link between visual and NIF effects of light. As such, the impact of light on visual comfort was investigated with respect to both effects. It was expected that a more comprehensive scientific basis for the definition of ”healthy lighting” at workplaces could be created, to be used by practitioners in a rather short future.

Chapter 2 Problem statement

2.1 Principles of visual comfort

The definition of visual comfort has been extensively debated for more than half a century without a universally accepted version. It has generally been defined as a lighting situation in the absence of visual discomfort [21, 22]. However, this definition is still insufficient to define visual comfort for several reasons:

- A lighting situation that provides better visual comfort is not necessary related to higher luminous intensity, while the latter is associated with higher task visibility [21, 22].
- People can tolerate glare sensations (as a cause of visual discomfort) from a daylighting condition better than from an artificial lighting condition [23].
- Visual comfort can change over time while the causes of visual discomfort do not differ (as tested under artificial lighting conditions) [17, 24].

Generally, the term 'comfort' indicates the perception of well-being and aesthetics [25] and the term 'visual' relates to 'seeing' or the sense of sight. In this work, 'comfort' could thus be defined as [26]:

- The absence of discomfort
- Positive feelings of well-being
- A pleasant state of physiological, psychological and physical harmony of a human being with her/his environment ([27]referenced in [28]).

According to the above statements, lighting conditions should avoid causing visual discomfort. What are the causes of visual discomfort?

Since the visual system perceives 'information' from a visual environment, the aspects that interrupt the abilities of 'information' perception can be defined as potential causes of visual discomfort, such as visual task difficulty, under- or over-stimulation by light exposure in a scene, distraction within the visual field and perceptual confusion due to the luminance distribution [21]. After excluding the causes of visual discomfort, a lighting condition with optimal visual comfort may lead to positive feelings in terms of lighting preferences, aesthetics, brightness, or well-being. Moreover, the 'comfort' sensation is known to be affected by physiological and psychological interactions of humans with their environment [28]. Visual comfort should therefore also comprise lighting conditions optimized for human psychological and physiological well-being which means not only visual functions but also Non-Image Forming

(NIF) effects of light. With respect to the latter, the lighting conditions should maintain optimal sleep-wake homeostasis in humans. Healthy lighting conditions mean not only luminous conditions during daytime; they concern also optimal light (if necessary) during dark periods for the sake of good health.

This doctoral thesis is mainly focused on the impact of light on visual comfort as opposed to visual performance. One reason is that it is the most effective method to determine lighting quality due to the fact that the changes of visual comfort are more sensitive than those related to visual performance *per se* [29]. Although optimal visual comfort enhances visual performance, uncomfortable lighting conditions do not always reduce visual performance ([30, 31] as referenced in [22]).

At present, visual comfort cannot be objectively quantified due to the fact that no empirical model of visual comfort is generally accepted. Some numerical methods can however be used to determine luminous distribution within spaces. Moreover, the luminous distribution can be considered as a key factor for visual discomfort depending on glare and luminance ratios. Furthermore, lighting quality also needs to be assessed; this can be done with human subjects by applying subjective assessments. Until now, reliable human and physical factors referring to visual comfort are not well circumscribed: it is important to understand how lighting conditions can have an impact on visual comfort. Most of the published visual comfort assessment scales focus on lighting preference and light perception, many of them are finally resulting in visual performance assessments [20, 32-37]. 'Visual' performance means task performance which only relates to the visual system. However, 'task' performance can be influenced by both, visual and non-visual aspects [38]. Photometric variables, such as the luminous intensity, luminous distribution or colour appearance of light might also influence visual comfort. In order to combine these effects with subjective ratings, simultaneous lighting monitoring and visual comfort assessments are needed. A comparison between the physical properties of light and subjective assessments can foster a better comprehension of the fundamentals of visual comfort.

The next section describes the impact of office lighting on office workers. Visual discomfort, lighting preference, brightness perception and visual performance will be discussed based on results from the literature. Several findings from physical light properties, such as luminous distribution, luminous intensity, colour appearance of light and light sources (daylight vs. artificial light) will also be covered.

2.2 State of the art of research

2.2.1 Impact of lighting on visual comfort

Luminous distribution

Luminous distribution is a key factor underlying the causes of visual discomfort within workspaces. The ratio between the vertical plane illuminance and the work plane illuminance must be checked particularly in office rooms equipped with Video Display Terminals (VDT). According to the recommendations of the Illuminating Engineering Society of North America (IESNA) [22], luminance ratios between the task and their immediate surroundings must not exceed 1:3 (or 3:1) and should not be larger than 1:10 (or 10:1) for more distant surroundings. Similarly, the ratio between a VDT and its immediate and remote surroundings should not be larger than 1:3 and 10:1, respectively (see Figure 2.1). In addition, the luminance ratio outside the field of view must be lower than 1:40 [39].

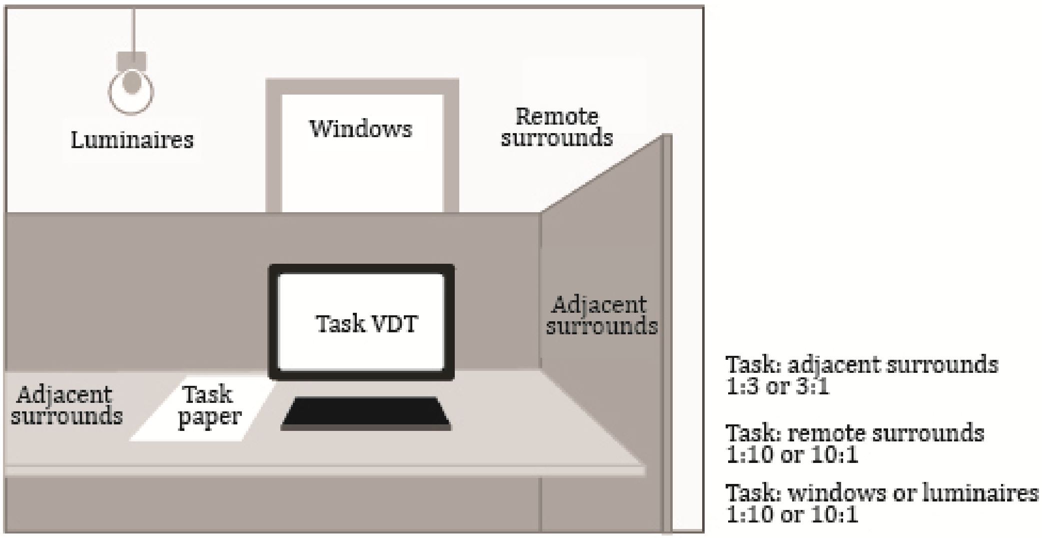

Figure 2.1: Maximal luminance ratios recommended by IESNA for VDT workstations (after [22] and [39])

However, La Toison [40] states that “objective contrast, such as the ratio of luminances (R; Equation 2.1), does not allow lighting situations to be characterized where the subjective aspect is dominant. Apparent contrast (C; Equation 2.2), as advanced by Bodmann [41] for discomfort glare, is completely different, since there is a difference in brightness”. This implies that the apparent contrast, which is generally used in formulae of discomfort glare (or glare indices), is more relevant for the assessment of visual discomfort than an objective contrast (or a luminance ratio).

$$R = L2/L1 \tag{2.1}$$

$$C = \Delta L/L1 \tag{2.2}$$

where L1, L2 are surface luminance of a given area (resp. task/background) [cd/m^2].

Discomfort glare can be induced by poor luminance distribution, generally caused by an extremely high luminance source, located in the field of view. Two main glare situations have been identified and described as: 1) excessive luminance contrasts in the field of view, and 2) (over-) saturation of the visual system. Excessive contrasts are usually caused by very bright surfaces which are perceived in a much darker environment, such as a pocket light spot on the floor in a cellar. Saturation affects the visual system, when the retina is stimulated by a too large flux of light when for example a pocket light beam is oriented toward the eyes. Daylighting within buildings can induce either each of them in an individual manner, or the two situations together. Glare reduces visual performance by impeding certain visual tasks and is therefore called 'disability glare'. Besides, glare that leads to a sensation of annoyance, eye strain or pain without affecting visual performance is called 'discomfort glare' [42].

Both daylighting and artificial lighting conditions can cause discomfort glare, although occupants may tolerate daylighting and artificial lighting conditions in various degrees. Hence, there was a development of glare indices to assess the degrees of discomfort glare under a given lighting situation. Glare indices, as well as the way to calculate them using photometric variables, will be discussed in more details in Chapter 3.

Luminous intensity

In general, it has been invoked that lighting conditions leading to high task illuminance improve visual performance; nevertheless, this is not always the case for visual comfort. A study conducted by Muck and Bodmann investigated visual comfort and visual performance achieved for different task illuminance ([31]as referenced in [21, 22]). In this study, a group of young volunteers performed a visual task by identifying a specific two-digit number amongst hundred other numbers. The illuminance in this study varied between 50 and 2000 lx; higher work plane illuminance led to better visual performance and visual comfort in this illuminance range. Work plane illuminance exceeding 2000 lx led to a lower visual comfort and a higher visual performance at the same time. This implies that optimal visual comfort conditions are apparently associated with higher illuminance, but only to a certain level: when a certain illuminance threshold is exceeded, lighting conditions induce lower visual comfort.

Balder and colleagues also investigated visual comfort for different luminance values ([11] as referenced in [2]). The volunteers in this study were asked to qualify the lighting on their desks using three categories, namely, i) "too dark", ii) "good" or iii) "too bright". Figure 2.2 shows the results for each category of lighting. It can be seen that the largest fraction of "good" appraisals appears only when the luminance at the desk is close to 130 cd/m^2. This study experimentally confirmed that "good lighting" is not necessary the one showing the largest photometrical variables (e.g. luminance or illuminance). To obtain optimal visual comfort conditions, a lighting environment should balance all these variables.

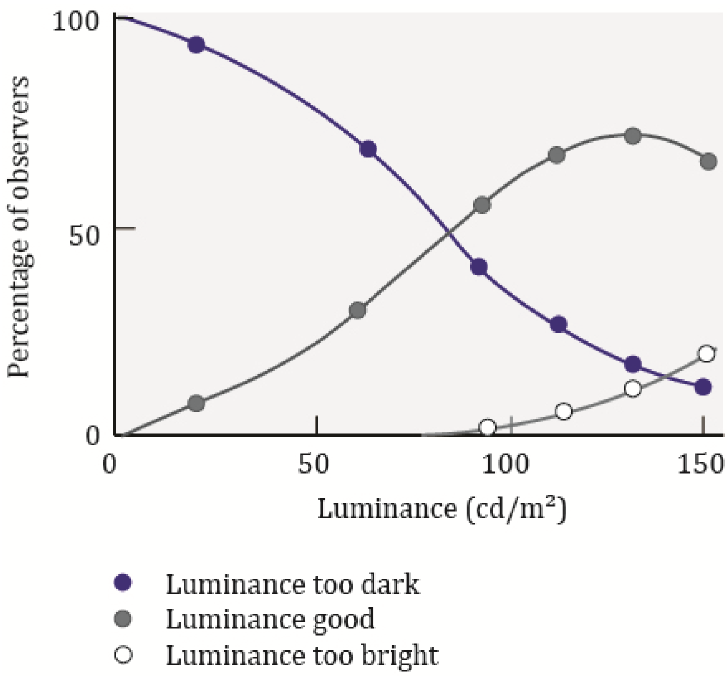

Figure 2.2: Relative fraction of observers rating their task lighting as "too dark", "good" or "too bright" for different luminance (cd/m^2) (after [30] referenced in [22]).

Colour appearance of light

The spectral composition of light sources determines the colour appearance of the light flux; it also influences indoor light perception. Generally, the colour appearance of a light source can be characterised by the way of the Correlated Colour Temperature (CCT) and the Colour Rendering Index (CRI) [43]. The light spectrum or the spectral power distribution of a light source is used as a metric in some studies; it indicates the colour characteristics of a light source for each wavelength over the visible part of electromagnetic radiation. More details about the colour appearance of light are given in Chapter 3.

So far, there has been little evidence to support the impact of light colour appearance on visual comfort; most studies only provide evidence of the impact of colour appearance on lighting preference or brightness perception (see Sections 2.2.2 and 2.2.3).

A study investigated the impact of street lighting on visual comfort between three different light sources with two types of metal halide lamps (CCT=2800K, CRI=83 and CCT=4200K, CRI=90) and a high pressure sodium lamp (CCT=2000K, CRI=25). In this study, the observers rated a higher visual comfort from the two metal halide lamps in comparison with the high pressure sodium lamp. Interestingly, no differences were found in comfort ratings between the light generated by the two metal halide lamps at 2800 K and 4200 K. It has to be noted that the CRI of the sodium lamp was very low (CRI=25) which might have induced an uncomfortable visual ambiance. The result of CCT is in agreement with another indoor lighting study which investigated the light appraisals of subjects from two different CCTs (same CRI=80) at 500 lx, 750 lx and 1000 lx from a work plane illuminance. The subjects rated a higher visual comfort and spaciousness with 4000K than with 2700K for all illuminance values.

However, this is contradicted by a study of coloured light sources, having aircraft passengers as participants. The study involved the use of multichip LED light sources which were set to four different colours. The first two types generated a yellow colour with centroid wavelengths at 603.2 and 607.1 nm, while the other two types generated a blue colour with centroid wavelengths at 496.8 and 504.6 nm. Unfortunately, there were no CCT or CRI data provided in the publication. The results show that the observers did not express different visual comfort sensations for the four different lighting conditions, even though they rated different perceptions of brightness and colour temperature sensations. They expressed the feeling of a 'darker' and 'warmer' atmosphere under the yellow light, while having the feeling of a 'brighter' and 'cooler' atmosphere under the blue light. Further research is still needed to understand the basics and impact of light colour appearance on visual comfort [44].

Daylight vs. artificial light

There is evidence that office occupants tolerate glare sensations from windows better than from artificial light sources [23, 45]; one main reason might be the different sizes of glare sources. This is the reason why daylight glare indexes were developed in a different way than those dedicated to artificial lighting. Many prior studies dedicated to office lighting involving daylighting found a strong bias in favour of views through windows within occupants' surveys. The results show that the further the occupants were seated from a window, the lower their satisfaction was [8, 46-48].

The view through windows can also lead to glare sensations and visual discomfort. [49, 50]. Tuaycharoen and Tregenza carried out an investigation under controlled laboratory conditions. In this study, volunteers had to rate 'interesting' view images projected on a small screen. The results show that a larger interest in the projected image was associated with a larger tolerance regarding discomfort glare [35]. The Unified Glare Rating (UGR), a glare index set-up for artificial lighting condition [51], was a poor predictor for discomfort glare in this case. The authors also conducted a study in a 20-floor building in Sheffield (UK) in order to investigate discomfort glare within identical office rooms at different floors and with different orientations. This study compared different window views between an opaque wall (no view), urban scenes (low-scoring view), and the view on a landscape scene (high-scoring view). It appeared that discomfort glare ratings decreased when the interest for the view increased. Hence, two factors for a new daylight glare index were proposed: 1) the interest for the view and 2) the variations of luminance depending on the changing weather conditions. The authors developed an empirical equation for a novel glare index based on the Daylight Glare Index (DGI) which is more appropriate for daylighting studies [49].

On the other hand, a negative impact of daylight in the presence of windows was also found by Roche et al.; these authors reported that dissatisfaction with daylight was also expressed by occupants when the average daylight factor was over 5%, with complaints regarding the reflection from the sun and glare [48]. Another study by Aries shows that occupants, who were located closer to the windows expressed more thermal and glare complaints [46].

2.2.2 Lighting preferences for office workers

Luminous intensity

Although well-established international standards for illuminance exist [22, 52], only little is known about inter-individual and subjective light preferences of building occupants. The preferred illuminance on a horizontal work plane was reported to be either larger [53, 54] or lower [36, 55, 56] than 500 lx according to international recommendations [22, 57]).

Fotios and Cheal [58] reviewed the ranges of preferred illuminance from different studies, as illustrated in Figure 2.3. These authors examined preferred illuminances using an adjustment task, where participants could set their task illuminance according to their preference within the available illuminance range (so-called the "stimulus range"). Figure 2.3 illustrates the preferred illuminances and stimulus ranges of each study. Scholz et al. [59] as well as Boyce et al. [60] also investigated multiple stimulus ranges. Scholz et al. [59] determined the optimal task illuminance set for 50 anesthetists which was used in order to visualise larynxes during laryngoscopies. Three different types of discharge lamps were used in these studies, namely 1) vacuum, 2) xenon and 3) halogen lamps. Each light source provided different ranges of illuminance, e.g. 'vacuum' = 5-327 lx, 'xenon' = 11-2583 lx, 'halogen' = 10-2557 lx. Boyce et al. [60] observed the preferred illuminance in a windowless office which comprised two stimulus ranges (low: 7-680 lx, high: 12-1240 lx). They found that the preferred illuminances for the same room were different (low: 398 lx, high: 518 lx) due to the stimulus range. Veitch and Newsham [36], Moore et al., Boyce et al. [61] as well as Begemann et al. [62] also conducted different studies in office rooms, while an investigation of Junlèn et al. [54] was carried out in a windowless industrial work space. The average preferred illuminances and stimulus ranges observed in these studies are illustrated on Figure 2.3.

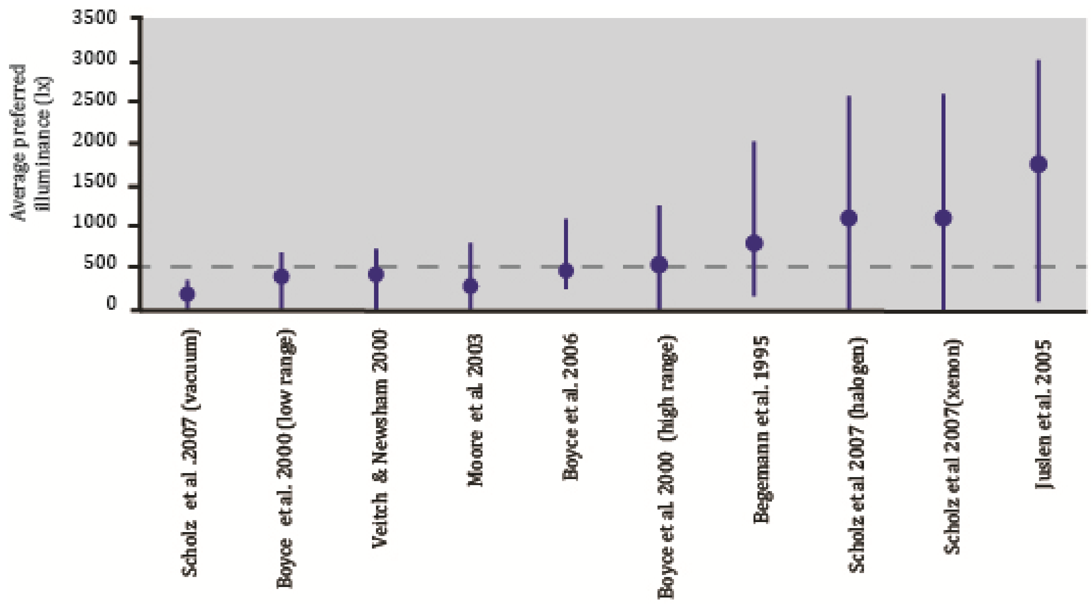

Figure 2.3: Summary of preferred illuminances from different studies (after [58]). The dashed line indicates the 500 lx on a horizontal work plan which is the minimum requirement at most working places.

According to their investigations, Fotios and Cheal argued that the average preferred illuminance is often close to the middle of the available illuminance ranges, the so-called "stimulus range bias". Interestingly, they also conducted another study, where the subjects were asked to evaluate their preferred illuminance from three different available illuminance ranges, namely, 1) low: 48-1037 lx, 2) middle: 83-1950 lx, 3) high: 165-2550 lx) [58]. The results supported their hypothesis that the average preferred illuminance approached the center of the stimulus range (for all three illuminance ranges). Logadóttir et al. [63] used a similar adjustment task and confirmed the results of Fotios et al. Furthermore, they noted that the initial illuminance used at the beginning of the study, the so-called "anchor", affected also the preferred illuminance: higher anchors settings (higher initial illuminance at the starting point) led to higher preferred illuminance [63].

Color appearance of light

It is generally argued that office occupants prefer high CCT light sources in the presence of high illuminance, and low CCT light sources in the presence of low illuminance. These findings were first reported by Kruithof [64] and were coined as 'Kruithof's law'. Figure 2.4 shows the range of preferred illuminance levels versus the CCT of different light sources. However, the original study has no data referring to the CRI of the light sources.

Many subsequent studies were not in agreement with the Kruithof's law. According to investigations by Davis and Ginthner [65], a relationship between CCT and lighting preference was not found. It seems that light preference is more associated with task illuminance [65] than with CCT. Boyce and Cuttle [66] reported that the CCT of lamps virtually had no effect on the observers' impression regarding lighting; higher illuminance led to a more positive appraisal regarding the room appearance which was qualified as more pleasant and more comfortable [66].

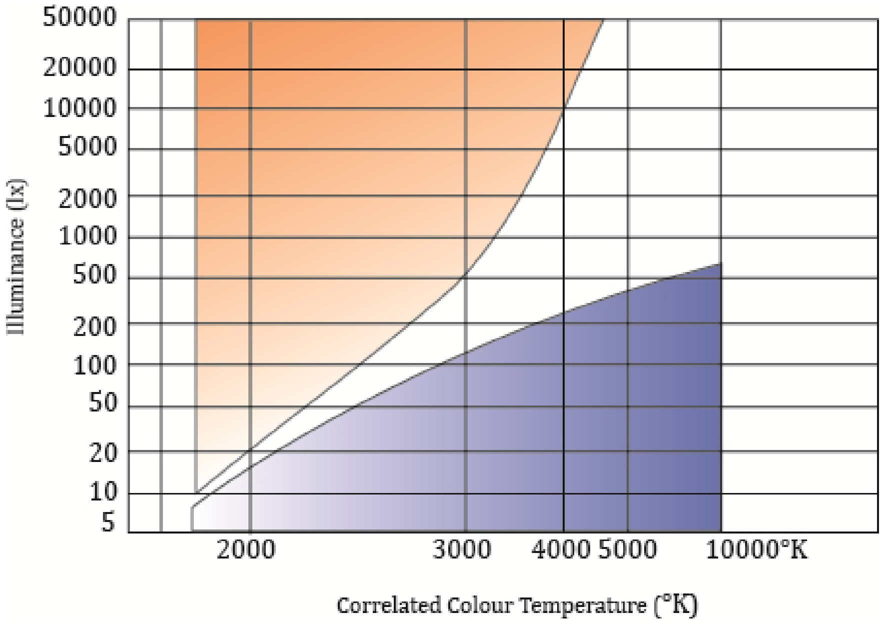

Figure 2.4: Kruithof's law as the association between CCT and illuminance of a given light source: the x-axis shows the CCT (K), and the y-axis shows illuminance (lx). The white area represents the illumination considered as being "pleasant". The lower blue section represents the illumination considered as "cold", while in the upper orange section the illumination is considered "unnatural" (after[64]).

It was found that colour rendering properties, rather than CCT, were the critical judgment variable for lighting conditions quality [67]. Correlations between CRI and lighting preferences were also found: higher CRIs are associated with greater light preference scores [68, 69]. Fotios and Cheal [69] evaluated the impact of lamp spectrum on lighting preferences by using side-by-side booths. The subjects had to determine the preferred colour appearance of their own hand (naturalness of the skin colour), of a colour chart (preferred colour appearance on the chart), as well as of an illuminated space from two identical models. The experiment employed five different lamp types: two different metal halide lamps (MH2, CPO), a compact fluorescent lamp (CFL2), a high-pressure sodium lamp (HPS) and two LED light sources with different colours. The lamps were equipped with a translucent diffuser in order to avoid differences in the spatial distribution of light; 14 points on the booths were maintained at constant luminances under the different light sources. Two booths were illuminated for comparative purposes using two different light sources of equal illuminance and brightness. The results showed that the CRI provided the strongest correlation with lighting preference ($R^2 = 0.85$), when compared to the Gamut Area Index (GAI), CCT, scotopic and phototic ratio (S/P) and the CIE mesopic system.

Daylight vs. artificial light

Access to daylight generally improves users' satisfaction with lighting; it is preferred to pure electric lighting conditions [8, 48, 70, 71]. It is widely known that daylight is more desirable for psychological reasons, environmental appearance and pleasure [71-73]. Daylight is rated superior to other light sources: it provides higher illuminance and allows a better colour discrimination and office appearance [71, 73, 74]. Some studies mention that a workplace located near the window is significantly more attractive and higher ranked [8, 36, 46-48, 75, 76] than one located further in the room , due to the opportunity of a view through windows, as well as the ability to identify the weather and to “open the window” to increase ventilation [75]. However, windows also showed negative impacts for those people sitting nearby, such as glare, thermal discomfort and lack of privacy [46, 48, 76].

Begemann et al. conducted a study with 96 occupants in their usual office lighting environment during daytime working hours [53]. They found that under daylighting conditions, the preferred workplane illuminances were much higher than the values recommended by current indoor lighting standards (500 lux at desk), which significantly correlated with the biological stimulation (as assessed by subjective sleep quality). The authors finally concluded that ‘biological’ lighting needs were very different from visual requirements. Another interesting finding of this study was that lighting preferences in combination with task visual performance varied strongly among individuals. Since then, several studies investigated inter-individual preferences and influences of light on biological functions [77-79].

Other physical lighting properties

Dynamic lighting for office spaces has recently been used in order to mimic the decreasing natural light at dusk and to achieve energy savings for electric lighting. Begemann [53] suggested that people preferred a lighting environment which follows the daylight cycle to steady state lighting [53]. Kort and Smolders [79] conducted a study about the dynamic lighting effect by setting a higher workplane illuminance and CCT in the morning and after lunch time and gradually modifying both lighting features after 9AM and 1PM (700 lx to 500 lx, CCT: 4700K to 3000K). Participants were more satisfied with the dynamic lighting conditions than with the steady lighting conditions of 500 lx and 3000K. However, they did not find any significant effects of lighting conditions on vitality, alertness, headache, eyestrains, sleep quality or subjective performance. Dynamic lighting conditions were also employed in another study for energy saving purposes. Akashi and Boyce [80] found that reducing the ambient office illuminance by about one-third did not cause a long-term modification of occupant satisfaction with the lighting environment. However, such a reduction in the ambient illuminance can still produce negative short-term reactions, which will fade as time passes due to the increasing perception of brightness [80].

2.2.3 Brightness perception

Luminous intensity

Brightness is a subjective assessment indicating ‘how much light’ is perceived by the human visual system; photometric measurements can lead to an objective assessment of the corresponding physical variables [81]. Brightness perception is a function of luminance; hence, it inevitably relates to the light intensity and the reflectance of the targets’ surfaces. Understanding the factors responsible for a brightness judgment can contribute to the design of more effective and efficient space lighting. As stated by Flynn et al., “…correct design attention to several ‘non-quantitative’ lighting factors (might) compensate in some degree for reduction in overall quantity of light"... ([82] referenced in[83]). Moreover, brightness perception also has an important impact on the feeling of safety within a space.

Colour appearance of light

Brightness does not depend only on illuminance; it is also a function of the colour appearance of light. It has been debated for more than a decade whether Spectral Power Distribution (SPD) of light sources has an impact on perceived brightness. Some studies demonstrated that SPD did influence brightness of room interiors or spatial brightness [80, 84-86], while it was not the case for other studies [65, 87]. Prior investigations proved that brightness perception was not depending on photopic sensitivity. Various indicators linking the colour appearance of light with brightness were suggested, such as CCT [80, 88], the colour gamut of light sources [86] or scotopic/photopic ratios [84]. It was reported that CCT, CRI, gamut area or chromaticity alone, can be good predictors of brightness. More recently, a mesopic luminous efficiency function was introduced to quantify the visual perception under low illuminance. This was done by bridging the scotopic and photopic luminous efficiency functions into a unified system of photometry [89]. Rea et al. suggested a model of brightness judgments based upon the short wavelength sensitive cone (S-λ) fundamental [90]. The colour of objects was also found to be relevant to brightness perception; however, it might not be influenced simply by their own luminance but by their colour contrasts against the background [91]. From this study was concluded that a new metric for spatial brightness is still required.

Luminous distribution

Luminance distribution in a room affects the brightness perception of an observer. One study used two types of office rooms with relatively uniform luminance distribution to assess perceived brightness. The office rooms were equipped with recessed fluorescent lighting with 1) acrylic lenses and 2) parabolic louvers. The offices with uniform lighting conditions were perceived at the same brightness as the office rooms with non-uniform luminance distribution, although the latter provided 5-10% less task illuminance. The results showed that the office rooms with non-uniform lighting conditions were perceived as brighter than the rooms with uniform lighting. The non-uniform rooms were, in this case, characterized by a larger luminance contrast between the brighter and darker wall portions leading to a brighter appearance.

2.2.4 Visual performance

Lighting conditions can impact human performance by three pathways: i) through the visual system, ii) through circadian effects, such as alertness (see Section 4), and iii) through the perceptual system, such as mood and motivation [1, 76]. Light is the key factor for visual performance via the visual system, while there are more factors concerned with the other two paths (the circadian and perception systems). Visual performance is affected by illuminance, luminance distribution and the spectral power distribution of light.

Luminous intensity

The range of light flux reaching the eyes during a day is large. In fact, sunlight generates a one-million-times higher luminance than moonlight, i.e. 100’000 lx vs. 0.1-1 lx. Naturally, the human eye has the flexibility to adapt to these various illuminance levels. Figure 2.5 illustrates schematically the scotopic, mesopic and photopic regions defined by Hurden et al. Photopic vision is linked to the V(λ) function (with a peak at 555 nm) reproducing the visual sensitivity of bright light conditions that stimulate the cone receptors. At very low illuminance, the eye’s spectral sensitivity is described by the V’(λ) function (with a peak at 505 nm) determined by the rod receptors in the scotopic region. The mesopic region covers a luminous range in-between the photopic and scotopic regions. In this region, the human eye is able to perform regular tasks, where both rods and cones are active. More recently, a new mesopic photometry (CIE mesopic system) has been introduced. It describes the spectral luminous sensitivity V_{mes} (λ) in the mesopic region as the linear combination of the V(λ) and V’(λ) luminous sensitivity functions based on the ratio of scotopic and photopic vision (S/P) [73]. The border line between mesopic and photopic vision is difficult to define, many factors, such as size and position in the view field, have also an influence on the latter [78]. Figure 2.5 illustrates the fact that certain tasks can restrictedly be performed in the photopic region due to colour discrimination and visibility.

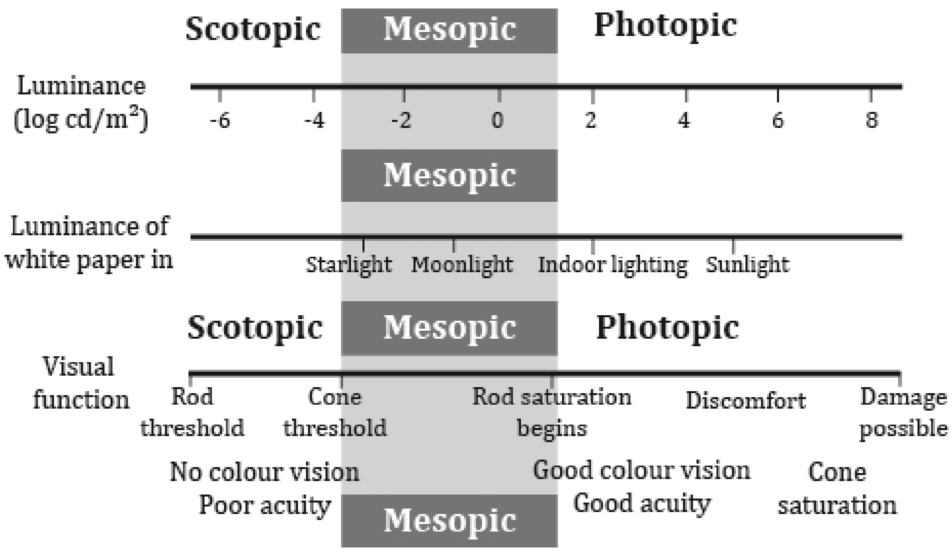

Figure 2.5: Schematic view of scotopic, mesopic and photopic regions modelled by Hurden et al. [92]

Luminous distribution

Rea [93] investigated visual performance under a constant illuminance (278 lx) with different luminance contrasts. He found that task contrast had a significant impact on task performance, as related to speed and accuracy [93]. Later on, he also used different illuminance ranges and found that visual performance increased at higher illuminance [94]. Finally, a Relative Visual Performance (RVP) model was developed in order to predict the visual performance, associated with task illuminance, task size and luminance contrast [95, 96]. The model was tested and validated [97, 98]; however, it can only be applied to tasks with images on the fovea and implies that the observers know where to look at, such as in the case of reading. The model can be used to assess visual performance without veiling reflections, disability glare and impact of the light spectrum.

Colour appearance of light

Colour might influence visual performance during a chromatic task, but there is still little evidence to support whether colour appearance of light significantly affects achromatic task performance. Besides, many studies failed to identify any effect of the light spectrum [85, 99-101].

However, Berman et al. demonstrated that the light spectrum influences visual performance under low luminance contrasts for achromatic tasks [102]. They studied the influence of different light spectra on the accuracy of task performance by using Landolt ring tests [102, 103]. Subjects had to assign the orientation of the opening of a C-shaped ring in one of the four cardinal directions, under differing background luminance. It emerged that young and older subjects had a better task performance under green-blue light sources (scotopically enriched illuminance; scotopic luminance = 228 cd/m^2), than under red-pink light sources (scotopically deficient illuminance; scotopic luminance = 13 cd/m^2) at the same photopic luminance (53 cd/m^2; Figure 2) [102, 103]. Given this phenomenon, increased scotopic luminance with an associated smaller pupil size, can lead to improved visual acuity [104]. The same authors also showed that pupil size, brightness perception and visual performance are linked to the ratio of scotopic and photopic lumen (S/P) [84, 104, 105]. Berman's theory implies that a lamp type with a larger proportion of short-wavelength (higher scotopic luminance) would lead to better visual performance. This was contradicted later on by other studies carried out under photopic conditions. Veitch and McColl [99] found no correlation between visual performance and the type of light source (studying fluorescent lamps with different light spectrums) for 200 lux task illuminance. Likewise, Boyce et al. found no impact of two different light sources (3000K vs. 6500K; 344 lux and 500 lux) on visual performance, although the spectral power distribution of light influenced the pupil size differently [85]. It is still questioned if the light spectrum operating through pupil size could have an impact on visual performance. Pupil size might be a small determinant of visual performance, which can be ignored for most lighting applications [106]. Only a little impact on performance of supra-threshold tasks was identified for practical lighting conditions (photopic region) [21].

Nevertheless, after the discovery of the novel class of photoreceptors, the intrinsically photosensitive Retinal Ganglion Cells (ipRGC), it has been demonstrated that the ipRGCs are responsible for some dynamics of the pupil reflex [12, 107]. It was found that a short wavelength luminous radiation at 460 nm ('blue' light) reduced the pupil size [12, 107] and led to a delayed post-illumination pupil response [108].

Daylight vs. artificial light

There is no empirical evidence that daylight, per se, is superior to other kinds of light sources regarding the work performance via the visual system. The great advantage of daylight is its quantity, the continuous spectrum and the luminous distribution. Some benefits of daylight for visual performance were identified when the task involved fine colour discrimination; this was hardly found in case of an achromatic task [109].

It appears that the findings of differing visual performance studies between office rooms with windows and windowless offices have so far been contradictory. According to a survey performed in an office building in Seattle (USA) [71], subjective work performances were similar for office occupants working with or without windows. The results show that most occupants preferred working under daylighting conditions [71]. However, Figueiro et al. [110] observed productivity of workers in a software development company in New York (USA). It was hypothesised that the occupants in the windowless office might not receive enough light flux to entrain their circadian system (see details in Section 4.1), seeking out for exposure to daylight and consequently spending less time in their offices (or seeking for more social interactions). The results showed that workers in windowless offices spent less time on computer tasks and more time talking on the phone than office workers in glazed offices [110]. The authors concluded that the occupants spent less time on tasks by spending more time talking to their co-workers; this might indirectly indicate that the office workers in windowless office were less productive than those benefitting from windows [110]. Other studies to be conducted in the laboratory and field studies to test the reliability and consistency of these results are still required to serve as a foundation for architectural practice.

2.3 Relevant questions and hypotheses

Visual comfort at the workspace has been investigated in the past with respect to glare, luminance distribution, luminous intensity and influences on visual performance. Beyond these visual effects, the lighting environment also impacts human physiology, behaviour and mood, mainly via a recently discovered novel class of photoreceptors in mammals, the ipRGC. Since then, it has become evident for indoor lighting to consider not only the quantity (e.g illuminance) but also the quality of light (e.g. the spectral composition). Nevertheless, the impacts of a lighting environment on visual comfort and the other aspects needs to be further investigated in terms of both daylighting and artificial lighting conditions.

This doctoral thesis aimed to effectively assess the impact of light on visual comfort, including both visual and non-image forming effects. The two main relevant questions for the non-image forming effects were:

i. How can the distribution of environmental light, its intensity and spectral composition be assessed more effectively inside of buildings?

ii. What is its impact on human visual comfort including visual and Non-Image Forming (NIF) effects?

The following hypotheses were derived:

- An appropriate device for monitoring luminance distribution must be efficient and accurate in order to investigate the luminance distribution simultaneously under realistic office lighting conditions, especially under dynamic daylighting conditions.

For the purpose of visual comfort assessments including non-image forming effects, the device must be able to monitor those distributions according to both visual and non-image forming effects of light.

The first question was answered by means of a novel photometric device used to monitor the luminance distribution within office rooms. It will be presented in Chapter 3.

To answer the second question, studies with human subjects were performed under different lighting conditions involving both daylighting and artificial lighting. During these experimental studies, the view through windows was excluded in order to limit the impact of the outdoor environment. Daylight, *per se*, as well as its photometric properties was examined with visual comfort, including the NIF effects. The results are presented in Chapter 5 and 6. The hypothesis with regard to the studies of impact of light on visual comfort, including both visual and non-visual systems, was the following:

- Inter-individual differences between subjects are expected, for example from different chronotypes or gender. Likewise, the change over time is also assumed to have an effect on the results of the studies due to the varying endogenous biological rhythms of the subjects.

In order to support the main hypotheses of this thesis, a conceptual model of visual comfort and light impacts was set up and illustrated in Figure 2.6 (following Figure 1.3 by Veitch et al. [18], presented in Chapter 1). Light has an impact on non-image forming effects, which includes acute light effects, circadian rhythms or the physical and behavioural changes during a 24-hour cycle, which are explained in Chapter 4. It is known that light synchronises the internal body clock to the external 24-hour light-dark cycle on earth [111]. Hence, apart from visual comfort and perception, light also impacts our physiology via the circadian system which is also included in this new conceptual model of visual comfort. Figure 2.6 shows the light paths as well as the impacts of each physical property of light, such as luminous distribution, intensity and colour appearance. The main variables on which this thesis is focused are presented in the white boxes in Figure 2.6.

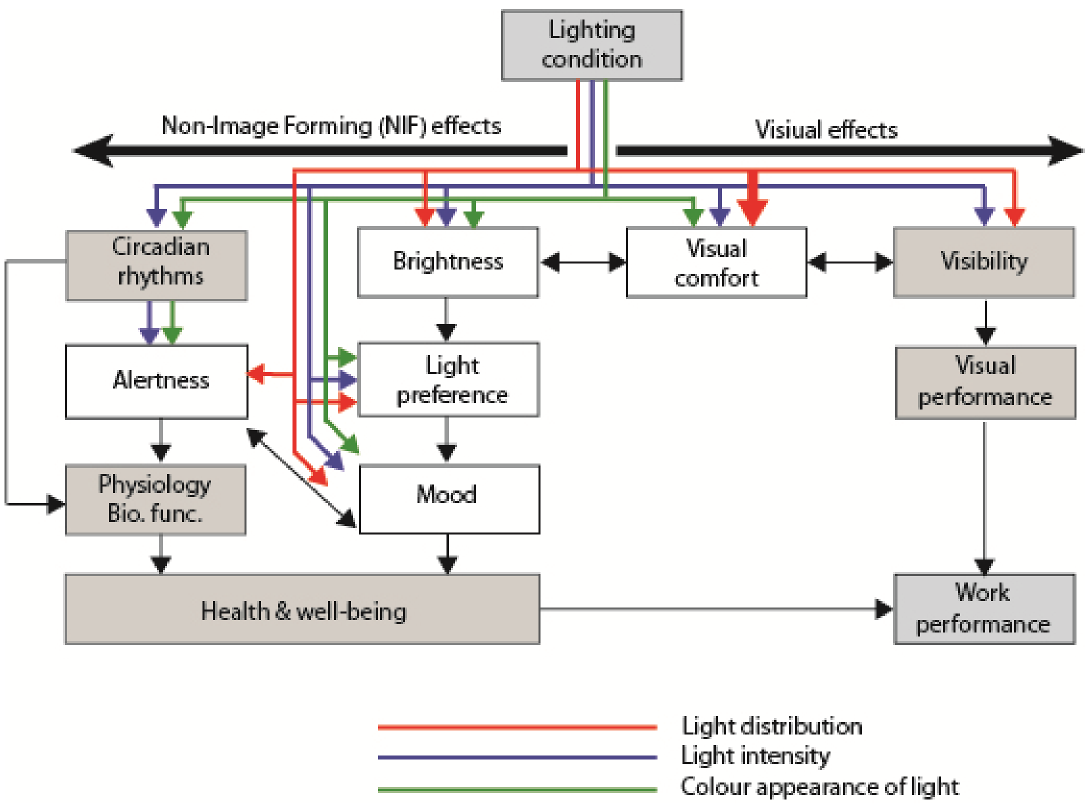

Figure 2.6: Conceptual model of visual and non-visual systems impacted by the different physical light properties of light: impact of luminance distribution (red), luminous intensity (blue) and colour appearance of light (green), constituting the main hypotheses of the doctoral thesis

The developed photometric device (issued from question i) was used during the experimental studies in order to examine the relation of luminance distribution with visual comfort, which might also impact other aspects of human eyes beyond vision. The hypotheses regarding the impact of light on visual comfort including NIF effects were formulated as follows:

- Since the lighting environment also influences the NIF effects, there might be some links between the visual system and the non-visual system, or visual comfort might directly relate to both systems. It is believed that light is first perceived, and then a given brightness is judged later on. In addition, light also directly affects subjective lighting preference and mood; light enhances well-being through the perception path. The circadian system is affected by light and also contributes to the improvement of health and well-being.

- Photometric variables are likely to greatly influence visual comfort and perception. Luminance distribution (shown in red in Fig. 2.6) is expected to influence visual comfort, brightness, light preference and mood. Luminous intensity (blue) and colour appearance of light (green) might impact all variables.

- Luminous distributions might also influence the NIF effects regarding visual comfort.

2.4 Structure of thesis

This thesis report is structured in the following way:

Chapter 1 gives an overview of the impacts of office lighting conditions on occupants. It introduces some open questions regarding healthy lighting criteria.

Chapter 2 reports the fundamentals of visual comfort. It presents the relevant questions and hypotheses of the thesis.

Chapter 3 describes luminance mapping techniques including the recent high dynamic range imaging technique. It also introduces the novel camera-like luminance sensor, which was developed and used in the framework of this thesis.

Chapter 4 reports the fundamentals of non-image forming effects. It also explains how light impacts the non-visual biological functions.

Chapter 5 reports the investigation of light effects on visual and non-visual functions according to two experimental studies.

Chapter 6 presents the visual comfort and luminance distribution assessed by the way of the novel camera-like luminance sensor.

Chapter 7 discusses the impacts of light on visual comfort including non-image forming effects. The conclusion intends to provide knowledge and give some suggestions for further research.

Chapter 3 Photometric measurements

3.1 Physical parameters

In order to understand the influence of light on human performance and behaviour, physical properties of the light sources have to be determined,- and measurements have to be performed by using appropriate metrics.

A light flux transports radiant energy and can be characterized using two different metrics reflecting its radiometric and photometric properties. Radiometric units define the properties of light in terms of quantities of absolute emitted electromagnetic radiation (from the entire spectrum). Photometric units define measures in the visible range of light, i.e. from 380-780 nanometres (nm). They are weighted by the sensitivity of the human rods and cones, since our eye is not equally sensitive to all wavelengths of electromagnetic radiation. Both radiometric and photometric metrics include four basic variables, illustrated in Table 3.1.

Quantity				Function
Radiometry (Unit)		Photometry (Unit)		
Radiant power	(W)	Luminous flux	(lm)	Total output flux from a light source (per time unit)
Radiant intensity	(W/sr)	Luminous intensity	(lm/sr = cd)	Flux emitted by a light source in a direction per unit solid angle
Irradiance	(W/m^2)	Illuminance	(lm/m^2 = lx)	Amount of light falling onto a surface at a certain distance from the light source
Radiance	(W/m^{2}sr)	Luminance	(cd/m^2 = nit)	Amount of light emitted by an element of the area of a light source in a given direction per unit solid angle

Table 3.1: Radiometric and photometric variables, as summarized from reference [112]

Photometry is usually based on photopic vision described by the human eye sensitivity curve designated by the V(λ) function; it is used in photometry as an average action spectrum for photopic responses following the CIE luminous efficiency function [113]. At very low illuminance, the CIE scotopic luminous efficiency V'(λ) function defines the action spectrum for the scotopic response [113]. Figure 3.1 presents the V(λ) and V'(λ) functions across the visible electromagnetic spectrum of light (from 380 to 780 nm). Moreover, in between photopic and scotopic regions, a new CIE mesopic curve has been recently introduced to describe the spectral luminous efficiency for the mesopic region [89], as mentioned in Section 2.2.4. In order to characterize the response of the human eyes in the mesopic region, the ratio of luminous quantity according to the scotopic and photopic visions (S/P ratio) is used. Mesopic Adaptation Luminance (MAL or L_{MES}) can be determined using the S/P ratio for different luminance values in the range of 0.01-3 cd/m^2 [89]. Large S/P ratios indicate a higher luminous efficacy of the light source with respect to the mesopic sensitivity in humans. Since the mesopic region is dynamic and depends on previous light and dark adaptation [114], the S/P ratio determines the L_{MES} values for different luminances [89].

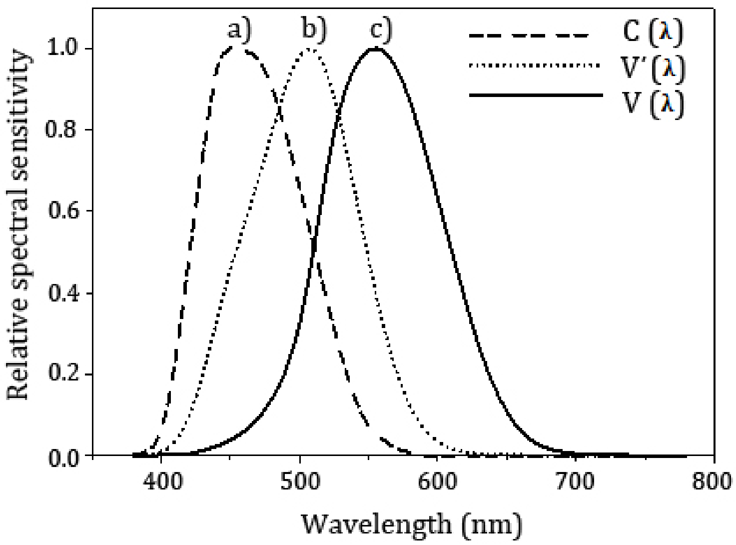

Figure 3.1: Relative sensitivity functions: a) circadian sensitivity function C(λ)[115] (dashed line); b) scotopic luminous efficiency function V'(λ) [89] (dotted line); c) photopic luminous efficiency function V(λ) [89] (solid line).

Besides the scotopic and photopic luminous efficiency curves, a circadian sensitivity function has been recently introduced. It is based on the relative sensitivity of a new class of photoreceptors located in the retinal ganglion cells, the so-called intrinsically photosensitive Retinal Ganglion Cells (ipRGC) [116, 117], showing a maximal sensitivity around 480 nm in the blue range of visible light. The ipRGCs are known to convey many so called Non-Image Forming (NIF) functions such as circadian rhythms, pupil light reflexes, and hormonal secretion [11-15]. Prior research showed larger induced nocturnal melatonin suppression in humans with narrow-bandwidth blue light (446-477 nm) [118, 119], indicating that melatonin suppression is an indirect sensitivity marker of ipRGCs. A few research groups suggested their own circadian sensitivity curves [115, 120, 121] based on melatonin suppression data, first published by Brainard et al. [118] and by Thapan et al.[119]. A relative circadian sensitivity function C(λ), illustrated in Figure 3.1, was proposed by Gall [115], who also suggested three new metrics in order to quantify the circadian effects of light sources: i) the circadian weighted irradiance E_{ec} (unit in W/m^2); ii) the circadian action factor a_{cv} (no unit) and iii) the circadian weighted radiance L_{ec} (unit in W/m^{2}sr) [122, 123]. Another research group, led by M. Rea (Lighting Research Center, Rensselaer Polytechnic Institute, NY, USA), also suggested a C(λ) curve based on human melatonin suppression data [120, 124]. According to their model, the terms 'Circadian Light' (CL_A) and 'Circadian Stimulus' (CS) were introduced as new circadian metrics [125].

Briefly, the CL_A is also a spectrally weighted irradiance (unit in W/m^2) and the CS transforms the CL_A into a relative unit from 0 to 1, in order to describe the effective photic stimulus of a light source for the circadian system [125]. A third approach for a circadian sensitivity function came from Kozakov et al. [126]. According to these authors, the maximal circadian sensitivity is close to 450 nm. Moreover, the "melanopic spectral efficiency function" or $V^z(\lambda)$ (the name melanopic refers to melanopsin, the ipRGC photopigment) with a peak sensitivity around 480 nm was recently introduced by the Lucas group (University of Manchester, UK). Based on this function, a "melanopic illuminance" (in 'm-lux') can be derived in order to measure the luminous intensity for the NIF effects in animals and humans [127, 128]. Besides circadian efficiency functions, the correlation factors of radiometric/photometric variables with circadian metrics were also recently suggested. Bellia and Bisegna [121] proposed two constant values, alpha (α) and beta (β), for different light sources as conversion factors for radiometric (α) and photometric (β) functions. Their suggested β value depends on the spectral power distribution of the light source. This approach has been proposed to lighting designers and practitioners in order to evaluate the circadian effect of light sources with 'easy to apply' parameters. However, to date, none of the above described circadian sensitivity functions have been incorporated into international lighting regulations; there is currently work in progress by several international institutions [129].

Even though there is not yet a formal circadian metric available to quantify the biological effects of light in humans, there are already devices for measuring light fluxes in circadian metrics based on existing sensitivity curves. Besides spectroradiometers with a circadian metric function, a few novel devices have been introduced as "personal exposure devices" in order to assess long-term light exposure for both visual and circadian spectral sensitivity. The "Daysimeter" (developed by the LRC, Rensselaer Polytechnic Institute, NY, USA) [130] contains two photosensors: a photopic detector and a shortwave (blue) light sensor; the latter is derived from the $C(\lambda)$ curve suggested by Rea et al. [124], as mentioned above. The device converts incoming light fluxes into illuminance, CL_A and CS. The "Daysimeter" comprises an accelerometer which monitors activity as well as an optical sensor array wired to a circuit board; it is available in two versions [131]: i) the "Daysimeter-S", a small head-mounted device, and ii) the "Daysimeter-D", with a micro clip to be pinned on the collar of a shirt. Both devices were validated simultaneously to record light exposure and activity rhythms from day-shift and rotating-shift nurses [132].

The second device, called "LuxBlick", was developed by Hubalek et al at ETH Zurich, Switzerland [133]. The "LuxBlick" includes two light sensors to record illuminance and blue light separately as well as a_{cv} mentioned above. Blue light and a_{cv} are circadian metrics derived from the $C(\lambda)$ curve by Gall [122]. The device can be fixed on spectacle frames in order to monitor daily light influx during an observation period. "LuxBlick" was used as a tool to investigate daily light exposures and their relationship with subjective sleep quality and mood in office workers during seven consecutive days. The results revealed the positive impact of light, including luminous exposure, duration and spectrum parameters, during daytime on sleep quality on the following night [134]. The measurements taken with office workers pointed to the fact that exposure to light on working days was rather constant, whereas it varied on the days off [134].

The last device, a wrist worn activity watch "Actiwatch Spectrum", is commercially available from Philips Healthcare (Eindhoven, NL) [135]. It can simultaneously record illuminance and spectral irradiance for red, green and blue (RGB) components via separate spectral channels. The equipment was used to investigate daily light exposures in humans across seasons as well as the relative red, green, and blue wavelengths content of these seasonal changes in photoperiods [136]. The accuracy for the photometric monitoring and RGB sensor system of the device were recently assessed [137]. The same study suggested to use a given fraction of the blue and green channels outputs for the monitoring of the “blue light” circadian action spectrum to be used as a circadian personal exposure device [137]. Another study compared the use of the “Actiwatch Spectrum” for circadian studies with the “Daysimeter” [131]. It resulted that the photometric performance of the “Daysimeter” was better than that of the “Actiwatch Spectrum”. The CIE standard error of the V(λ) function (designated by f_1’) [138] of the “Daysimeter” was equal to 25%; the corresponding value of the “Actiwatch Spectrum” showed a substantial difference with a f_1’ value of 83%. The authors argued that systematic errors in photopic sensitivity of the spectral sensors existed. They assumed that “Actiwatch Spectrum” potentially overestimates the light flux and thus led to measurement errors, especially for the blue spectrum, which is essential to assess the light impact on the human circadian system [131].

Besides absolute and photometric measurements, the perception of colours in work environments also influences lighting quality [79, 87, 139]. The most common techniques to assess the colour appearance are the Correlated Colour Temperature (CCT) and the Colour Rendering Index (CRI), used in various lighting applications to compare the colorimetric properties of different light sources. The CCT is a specification of the colour appearance of the light flux emitted by a lamp, relating its colour to the colour of a black body heated to a given temperature, measured in Kelvin (K) [22]. A higher CCT (over 5000K) relates to ‘colder colours’ and contains a larger fraction of short visible wavelengths (i.e. blue components), while a lower CCT (2700-3000K) is related to ‘warmer colours’ (i.e. those that contain more red and yellow wavelengths) [22]. The CRI is a quantitative assessment of the ability of a given light source to render colours similar to their colour appearance under a reference light source (i.e. usually daylight or an incandescent lamp). Higher CRI values indicate a better colour rendering for the light source, which are closer to “true” colours.

Lastly, the characterization of the luminance distribution in the view field is also important, as it is a key for visual discomfort assessment. Previously, luminance distribution assessments were performed using a luminance meter, by monitoring point to point the luminance of surfaces. A similar procedure is used for glare risk assessments: after determining point to point surface luminances, glare indices can be calculated using a given formulae (more details in Section 3.2). Recently, advanced methods for assessment of luminance distribution using the High Dynamic Range (HDR) imaging technique were employed (see Section 3.3). An HDR image is acquired by using several Low Dynamic Range (LDR) images, taken with different aperture exposures with a Charge-Coupled Device (CCD) camera. Using this technique, a ‘luminance map’ of lighting environments can be obtained [140-143]. The benefit of this technique is the ability of any CCD camera to capture detailed spatial information relating to luminance distribution in a given space. Another application of HDR imaging techniques is determination of glare risks with the help of available software, as described in detail in Section 3.3.3.

In the course of this thesis, an innovative device has been introduced in order to assess luminance distribution more rapidly and more efficiently. By using this device, it is no more necessary to capture several images: a single HDR image can be captured by the way of a snapshot. This is useful to assess dynamic (day-)light distributions as well as the properties of any light source in circadian metrics according to Gall's circadian sensitivity function [122]. The calibration and the validation of this novel luminance meter are described in Section 3.4. The application with circadian metrics is presented in Section 3.5.

3.2 Glare risks assessment

As mentioned before (see Chapter 2, Section 2.2.1), discomfort glare is an unwanted effect of excessive luminance contrast in the view field. Nowadays, none of the daylight glare ratings are unanimously recognized as an international standard. The most cited one is the Daylight Glare Index (DGI) which is a modified version of the glare index recommended by the Illuminating Engineering Society (IES): the IES glare Index (IES GI), suggested by Hopkinson for large glaring sources [144]. The DGI glare formula, expressed by Equation 3.1, was created for large area lighting sources, such as windows; its use was recommended for daylighting conditions [45].

$$DGI = 10\log_{10}\sum_{i=1} 0.48 \cdot \frac{L_{si}^{\ 1.6} \cdot \Omega_i^{\ 0.8}}{L_b + 0.07 \cdot \omega_{si}^{\ 0.5} \cdot L_w} \tag{3.1}$$

where:

n [-] is the number of glaring sources;
L_{si} [cd/m²] is the glaring sources luminance (i), such as the luminance of the visible sky patch, the obstructions and the ground perceived through the windows;
Ω_i [sr] is the solid angular subtended by the glaring sources (i);
L_b [cd/m²] is the background luminance, such as those of the room;
L_w [cd/m²] is the average window luminance weighted according to the relative areas of the sky and the ground;
ω_{si} [sr] is the solid angle of the luminous parts of each light source (i) as viewed from the observer's eye.

Several authors criticized the reliability of DGI, and other formulas for daylight discomfort glare assessments were suggested [145, 146]. Osterhaus et al stated that the direct vertical illuminance at the observer's eye (vertical illuminance at the eye) showed largest correlations with the subjective glare rating expressed by observers, compared to other glare indices, such as the CIE Glare Index (CGI), the Unified Glare Rating (UGR) and the DGI [147]. Recently, another glare index, the Daylighting Glare Probability (DGP) has been suggested by Wienold and Christoffersen [148], based on a glare risks assessment within an office room showing discomfort glare induced by windows. The DGP combined the vertical eye illuminance with a modified glare index given by Equation 3.2. It was used in recent lighting studies for evaluations of discomfort glare induced by windows [149-152].

$$DGP = c_1 E_v + c_2 \log_{10}\left(1 + \sum_{i=1} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{c4} P_i^2}\right) + c_3$$

(3.2)

where:

E_v [lx] is the vertical illuminance at the eye; $c_1 = 5.87 \times 10^{-5}$;
L_{si} [lx] is the luminance of source (i); $c_2 = 9.18 \times 10^{-2}$;
ω_{si} [sr] is the solid angle sustended by source (i); $c_3 = 0.16$;
P_i [-] is the Guth position index of source (i); $c_4 = 1.87$.

Another glare index, the Unified Glare Rating (UGR) recommended by CIE, is intended to be used for artificial lighting conditions and given by Equation 3.3 [153],

$$UGR = 8 \log\left[\frac{0.25}{L_b} \sum_{i=1} \frac{L_i^2 \omega_i}{P_i^2}\right]$$

(3.3)

where:

L_b [cd/m2] is the background luminance;
L_i [cd/m2] is the luminance of the brightest part of each light source (i) in the direction of the observer's eye;
ω_i [sr] is the solid angle sustained by the brightest part of each light source (i) at the observer's eye;
P_i [-] is the Guth position index of each light source (displacement from the line of sight).

The UGR formula is widely used for visual comfort analysis of office rooms with artificial lighting conditions. According to CIE recommendation, UGR values must not overcome an upper limit of 19 in office rooms equipped with work stations and Visual Display Terminal (VDT) (writing, typing, reading, data processing) [153]. Table 3.2 gives a comparison of the three glare rating scales, together with the associated glare sensations.

Glare Sensation	DGP	DGI	UGR
Imperceptible	<0.30	<18	<13
Perceptible	0.30-0.35	18-24	13-22
Disturbing	0.35-0.45	24-31	22-28
Intolerable	>0.45	>28	>28

Table 3.2: Criteria of glare sensations assessed by the DGP, DGI and the UGR scales (after [149])

Glare indices, such as the DGI, DGP and UGR can be assessed using luminance mappings based on the HDR technique employed in photography (see Section 3.3) or HDR image renderings generated by computer simulations. The software 'RADIANCE' [154] provides specific codes for that purpose such as: ‘Findglare’, ‘Glarendx’ [10] and ‘Evalglare’ [148]. These functions can be used for HDR digital image renderings. Thus, by means of HDR imaging techniques, potential glare sources are first identified on the images, and in a second step the corresponding glare index calculations can be executed. The glare assessment based on HDR techniques is described further in the next section.

3.3 High Dynamic Range (HDR) imaging techniques

3.3.1 Background

The human visual system can cope with light intensities which vary over 10 orders of magnitude [155]. It is capable of simultaneously adapting to contrasts over a range of five orders of magnitude within a scene [156]. An ordinary digital 8-bit image is characterized by a much lower luminous dynamic range. A Low Dynamic Range (LDR) image cannot provide sufficient details of the real scene, especially in shaded or overexposed regions. Thus, the pixel values of an LDR image do not correspond to the luminance values of the real scene. Conversely, HDR imaging techniques can capture the full dynamic range of real scenes. A single HDR image can be generated by fusing a sequence of LDR images under different exposure intervals, taken by a Charge-Coupled Device (CCD) camera. As a result, each pixel data can be merged by using a response curve derived from this set of images. An algorithm that recovers the response curve of the CCD camera allows obtaining an accurate radiance value for each pixel [157]. Luminance mappings can be produced using any available open source software, such as hdrgen [158], RADIANCE [159], Photosphere [160], or by accessing the WebHDR HTML [161] (which uses hdrgen as a back-end).

3.3.2 Calibration of HDR Images

In order to empirically calibrate an HDR device, luminance values assessed by HDR imaging techniques must be compared with those monitored point-to-point by a luminance meter; this is generally done to determine the accuracy and reliability of this technique [140-142, 151]. Figure 3.2 shows the experimental set up used for that purpose, based on a CCD camera (Nikon Coolpix 5400, Tokyo, Japan) which is equipped with an FC-E9 fisheye lens (Nikon, Tokyo, Japan), a calibrated luminance meter (Minolta LS110, Tokyo, Japan), tripods and targets (Macbeth® colour chart, X-Rite, Michigan, USA), as previously reported [151]. Relative errors can be determined by comparing the device output with a conventional point-to-point luminance meter. Most studies showed that this technique provided very reasonable 10-20% relative accuracy for a wide range of luminance (0.5– 12,870 cd/m^2) [140, 142].

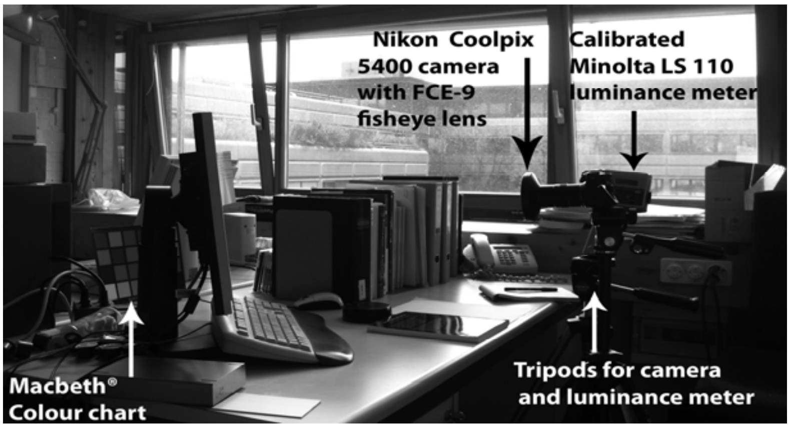

Figure 3.2: Experimental set-up comprising a Nikon Coolpix 5400 CCD camera equipped with a FCE-9 fisheye lens, a calibrated Minolta LS 110 luminance meter and tripods. The luminance calibration was made at defined target points within the room using a Macbeth Colour Chart [151].

3.3.3 Practical applications of luminance maps

Luminance ratio calculation

The luminance of a given surface can be extracted using one of the above mentioned pieces of software (see Section 3.3.1). In the next step, the luminance of different task areas and surroundings can be obtained and luminance ratios calculated. To assess the task luminance or the surroundings of a specific location in a more precise manner, certain areas can be masked using image processing software, such as Adobe Photoshop® or an open source as GIMP. Using "pcomb" and "pvalue" commands in RADIANCE [154, 159], each masked area can be processed in order to determine its average luminance value [151]. Figure 3.3 illustrates the masks of different areas as obtained by the image-processing software Adobe Photoshop® [151].

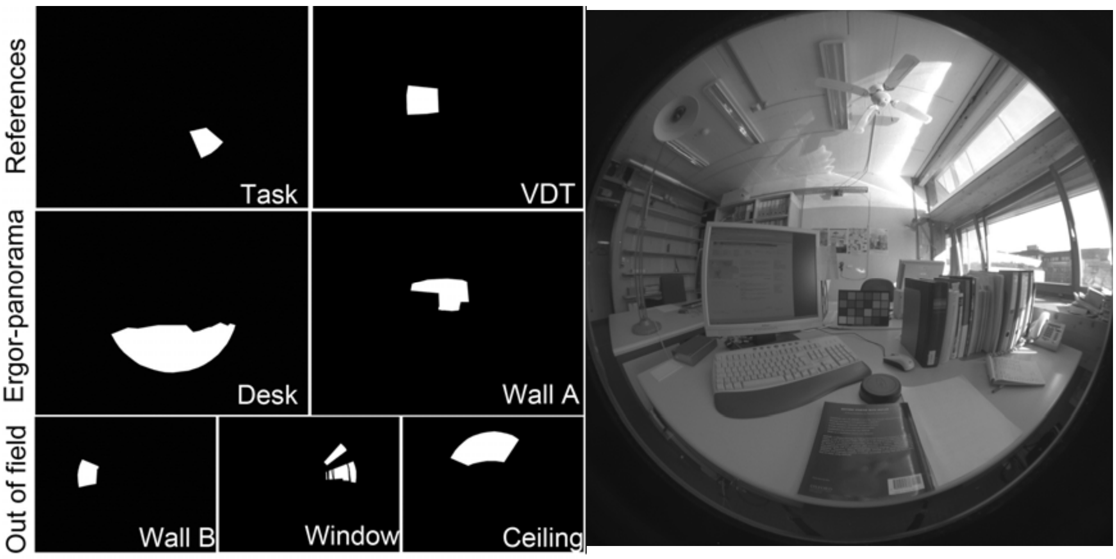

Figure 3.3: Marked areas of the reference task areas and their surroundings in an office room by using masking functions for the assessment of luminance ratios [151].

Glare indices calculation

Glare indices in the occupants' field of view can be calculated through HDR images using the 'Evalglare' in RADIANCE routines [148, 159]; moreover, 'findglare' in the software RADIANCE is also applicable [154]. Several parameters of the glare formula, such as the luminance background, glare source luminance and solid angles can also be determined using HDR imaging technique; luminance values can be extracted for each pixel from the luminance mapping. Potential glare sources are identified by being detected on the basis of a luminance threshold value [160, 162]. This way, DGI, UGR, DGP as well as other glare indices can be calculated.

Figure 3.4 shows pixels of potential glare sources, as circled by the RADIANCE software using the 'findglare' and 'glarendx' commands. Applying 'Evalglare', irregular shapes of potential glare sources can also be detected and coloured as shown in Figure 3.4 b). Moreover, the task area can also be manually defined; contrasts between task areas and potential glare sources can then be calculated more precisely. In the course of the thesis, the glare indices were determined using 'Evalglare', which will be presented in Section 3.4.3 and in Chapter 6.

Figure 3.4: Glare risk assessment using: a) RADIANCE with 'findglare' and 'glarendx' commands [159] and b) 'Evalglare' [148, 162]

3.3.4 Limitations of HDR imaging techniques

Glare risk assessments and luminance mapping can be accurately performed by the way of HDR imaging techniques. However, a non-negligible time lap is required for image capturing and post processing. In order to achieve luminance maps, a number of LDR photographs are needed in order to generate the full dynamic range of luminance in the scene: the LDR images must cover the range of minimal and maximal luminance values of the considered scene. A large number of pictures leads to a better signal-to-noise ratio. The procedure is time consuming since several images have to be collected by the way of a conventional CCD camera to produce a single HDR picture. Another disadvantage is the difficulty to cope with dynamic daylight conditions: the luminance distribution of a daylit scene might change while taking those images. Dealing with highly dynamic and contrasted daylighting environments always result in rapid changes of the different glare indices due to the variable luminance of the sun and the sky vault. It would therefore be better to capture images more rapidly, especially under dynamic daylight conditions. To achieve this goal, a newly developed Camera-Like Light Sensor (CLLS) was used in the course of this thesis (see Section 3.4). It aims to produce faster HDR images and to simultaneously assess glare risks under varying (day-) lighting conditions.

3.4 The Camera-Like Light Sensor (CLLS)

3.4.1 Principles of the device

The Camera-Like Light Sensor (CLLS) was developed by the Centre Suisse d'Electronique et de Microtechnique (CSEM; Neuchâtel, Switzerland). The original model, "IcyCAM" (Figure 3.5a), was introduced for the purpose of security surveillance, optical character recognition and industrial control [163]. The essential elements of this device are the intra-scene dynamic range of the optical front-end and a data representation that is independent from the illumination level. It contains a 'system-on-chip' (SoC) combining an optical front-end and a processor on the same device. The SoC enables a single chip to perform image acquisition, analysis and decision-making [164]. Each pixel achieves a 132 dB intra-scene dynamic range due to a logarithmic compression [163]. The logarithmic encoding allows one single HDR image to be real-time recorded in 780µs to 2s exposure durations [165]. According to its intra-scene dynamic range function, the CLLS provides a recording of images in real time. HDR images with much greater speed performance than the 'Classical HDR' technique of a conventional CCD camera can be recorded accordingly. The CLLS can capture an image (or a video) and present it in: i) classic (luminance) mode (Figure 3.6 a), ii) contrast mode (Figure 3.6 b) and iii) direction mode (Figure 3.6c). The contrast mode represents the contrast magnitude of an image; the direction mode shows the orientation contrast of eight directions.

The aim in this thesis was to use the CLLS device for dynamic luminance mapping and glare risks assessments. The CLLS was first calibrated for that purpose for photometric measurements; the corresponding calibration procedure according to the photopic spectral luminous efficiency function V(λ) is described in Section 3.4.2. In order to extend the field of view to approximately 154° X 115° which is close to the human visual field (~ 120° x 120° for the panorama [26, 155]), the CLLS was equipped with a Fujinon fish-eye lens FE185C057HA [166] (as shown in Figure 3.5 b); the vignetting effects were also corrected (see Section 3.4.3).

The following section describes the calibration and the validation of the CLLS for photometric purposes. The results were presented at the SPIE 2012 conference and reported in the SPIE conference proceedings [167].

a) b)

Figure 3.5: a) The original IcyCAM developed by CSEM; b) the IcyCAM equipped with the fisheye lens

a) b) c)

Figure 3.6: Image taken by CLLS with three different view options; a) the default image with the option "luminance", b) image with the option "contrast "and c) image with the option "orientation" .

3.4.2 Calibration procedure

Spectral Sensitivity calibration

In order to match the spectral sensitivity of the CLLS to the human eye (according to the photopic sensitivity function), the CLLS spectral response was determined and then corrected by three customized filters at the optimal thickness. The calibration was set up as shown in Figure 3.7, based on measurements performed previously in our laboratory [168]. Narrow bandwidth monochromatic light beams (generated by a 1000 Watt Xenon lamp and a grating monochromator) were used as a reference light source. The CLLS and a calibrated spectroradiometer (Specbos 1201, JETI, Jena, Germany) monitored the emitted radiance on the same target in an integrating sphere. The reference light source (monochromatic light source) was set at a 555 nm wavelength (using the monochromator), corresponding to the maximum of the photopic sensitivity curve, for different luminous intensities.

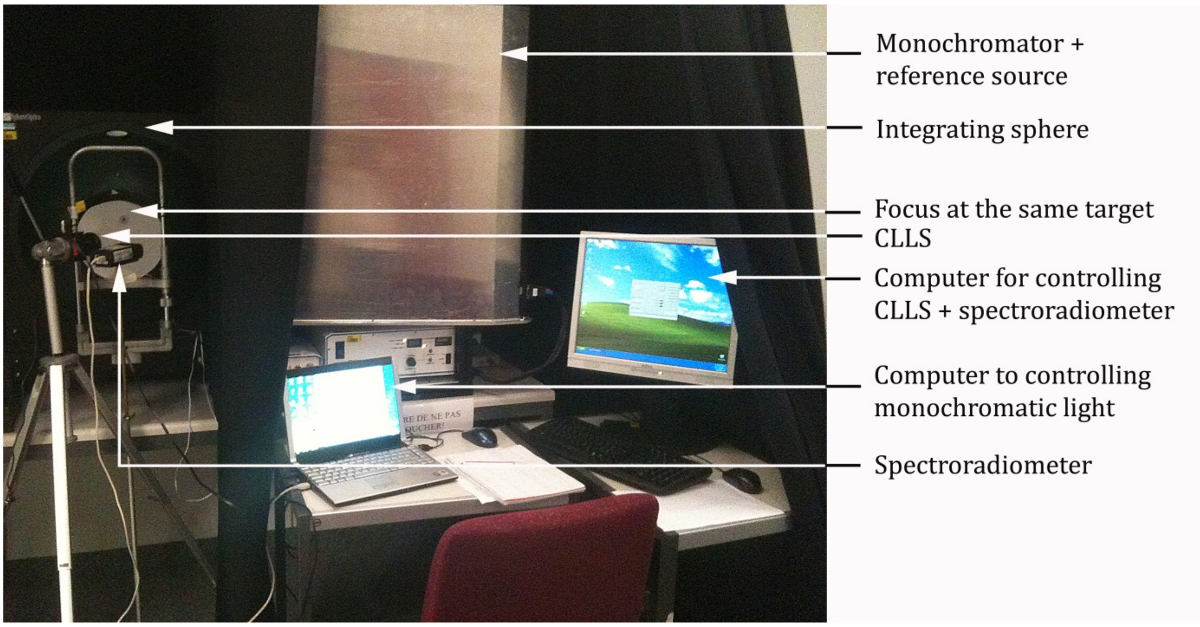

Figure 3.7: Experimental set-up for the spectral sensitivity calibration. The luminance meter, the spectroradiometer and the CLLS were placed in front of an Ulbricht sphere; the same target was aimed using the "spot laser" of the spectroradiometer. The irradiances were measured using the spectroradiometer; simultaneously, images were captured by the CLLS.

The CCLS digital camera provided one value per pixel on a grayscale (in arbitrary units from 0 to 1024 digits), while the spectroradiometer measured the corresponding radiance (in µW/m^2.sr)[168]. Equation 3.4 was used to describe the relation between grayscale values and monitored radiances (R^2 = 0.9994).

$$y = 1.36 \cdot 10^{-13} \cdot x^5 - 5.71 \cdot 10^{-11} \cdot x^4 + 1.29 \cdot 10^{-8} \cdot x^3 - 9.51 \cdot 10^{-7} \cdot x^2 + 6.76 \cdot 10^{-6} \cdot x + 1.83 \cdot 10^{-4} \qquad (3.4)$$

In a next step, the luminous intensity was kept constant; the same measures were then taken with the CLLS and the spectroradiometer, the wavelength of the light beam being modified using 5 nm steps from 380 to 780 nm. The relative raw spectral sensitivity of the CLLS is shown in Figure 3.8a, together with the standard V(λ) photopic luminosity function suggested in 1931 by the CIE [169]. Three coloured glasses were selected as filters: Kopp 3307, Kopp 3384 and Kopp 7071 (Kopp Glass Inc., PA, USA). Their optimal thickness was determined in order to match the spectral response of the CLLS with the photopic sensitivity function V(λ). After implementation of the filters on the CLLS, the previous procedure was repeated to obtain a sensitivity curve which corresponds to the V(λ) (Figure 3.8b). In order to assess the error between the relative spectral sensitivity of the CLLS and the V(λ) curve, the CIE standard error f_1' [138] was determined using Equation 3.5:

$$f_1' = 0.93584 \int_0^{\infty} |S(\lambda)_{rel} - V(\lambda)| \, d\lambda \qquad (3.5)$$

The corresponding standard error is equal to 8.3%. Based on the requirements from standard organizations (DIN 5032 [170]), the maximally tolerated error for commercial devices corresponds to f_1' = 9% ([170], cited in [133]); the error obtained from CLLS, after spectral calibration lies within an acceptable range.

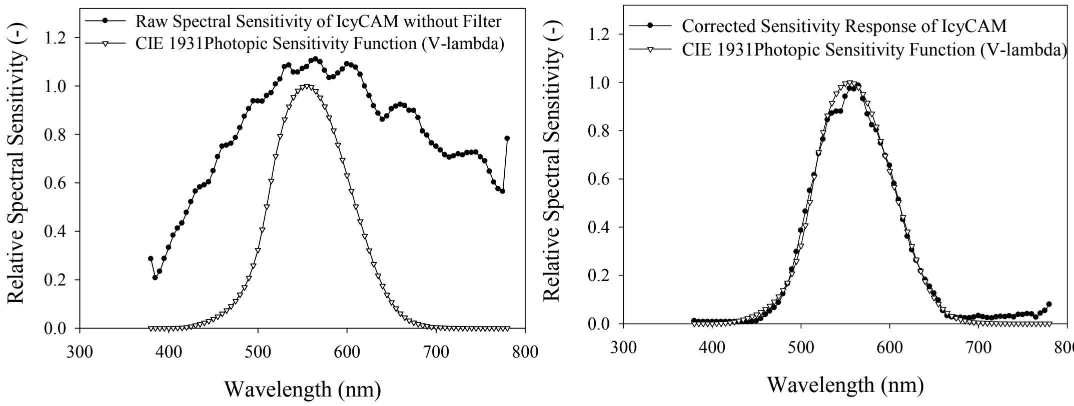

Figure 3.8: Relative spectral sensitivity assessments of the CLLS [167]; a) relative raw spectral sensitivity of CLLS (filled circles) shown with the CIE 1931 photopic sensitivity function [169] (V(λ); open triangles); b) corrected spectral sensitivity response of the CLLS equipped with filters (filled circles) shown with the CIE 1931 photopic sensitivity function [169] (V (λ); open triangles), within the visible range.

Photometric calibration

To perform a photometric calibration, a total of 138 measurements (from 0.01 cd/m² to 15,560 cd/m2) were carried-out by using the CLLS simultaneously with a calibrated Minolta LS-110 luminance meter (Konica Minolta, Tokyo, Japan), as well as a calibrated spectroradiometer (Specbos 1201, JETI, Jena, Germany). Polychromatic white light from a 1000 W Xenon lamp and a 1200 W metal halide spotlight were used as reference light source for the photometric calibration. The experimental set-up is shown in Figure 3.9.

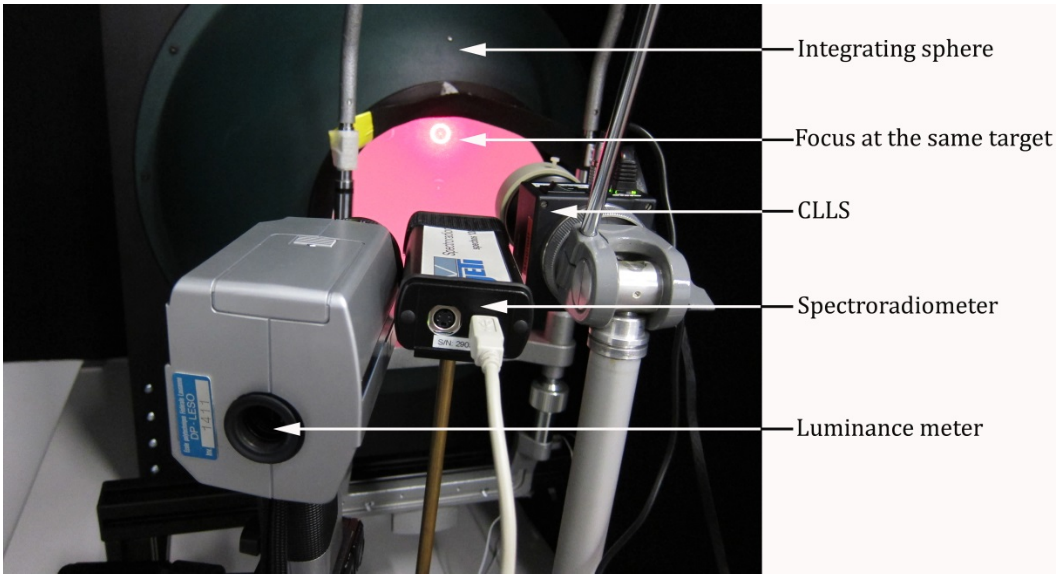

Figure 3.9: Experimental set-up for the photometric calibration. The luminance meter, the spectro - radiometer and the CLLS are aiming at the same target. The latter was located using the “spot laser” function of the spectroradiometer. Luminances were simultaneously measured by the luminance meter, the spectroradiometer and by the way of CLLS images.

The reference luminance values were obtained by the calibrated luminance meter. The camera provided the associated pixels on a greyscale (in arbitrary units from 0 to 1024 digits) and the luminance meter the corresponding luminance (cd/m²). The correlation between the pixel grayscale digits and the luminance values is illustrated in Figure 3.10. The luminance was associated to the greyscale [168] by an exponential fitting function, as given by Equation 3.6. The corresponding coefficient of determination is high: R^2=0.97.

$$y = e^{0.017x} \tag{3.6}$$

The exponential function was implemented in the "ImageCAM" software and was developed by LESO-PB, EPFL (Lausanne, Switzerland), in order to support the luminance mapping function of the CLLS [167].

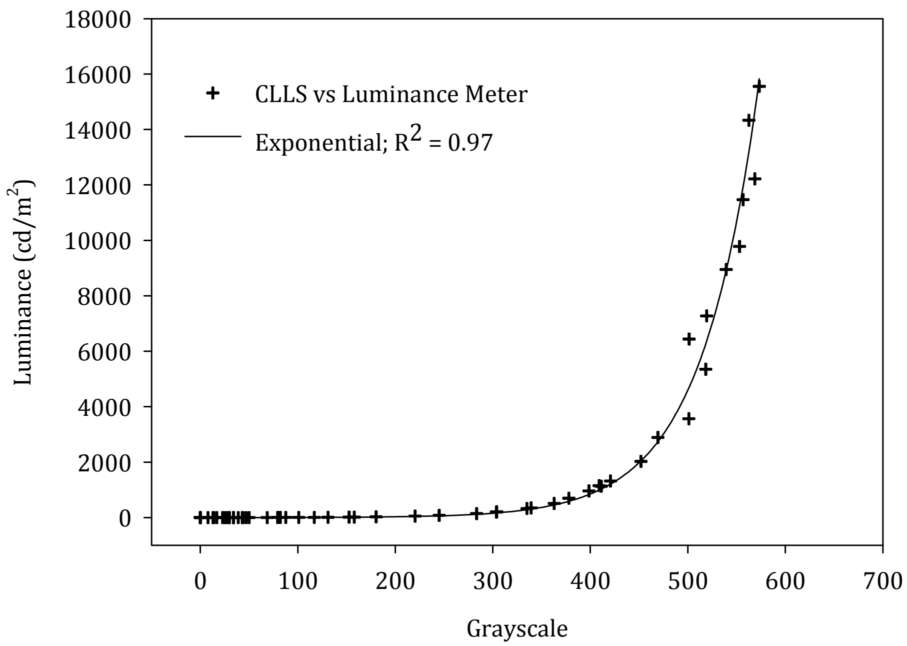

Figure 3.10: Correlation between the pixel grayscale values and the associated luminances. The black crosses indicate the measurements; the solid line indicates the fitted exponential function [167].

Vignetting correction

A Fujinon fisheye lens (index "FE185C057HA") [166] was installed on the CLLS in order to mimic the field of view of a human eye (≈ 120° x 120°) [1, 155]. Fisheye lenses normally exhibit noticeable light falloffs (so-called vignetting effects) for image pixels located far from the optical axis. Figure 3.11 illustrates the vignetting effect of the CLLS equipped with the Fujinon fisheye lens.

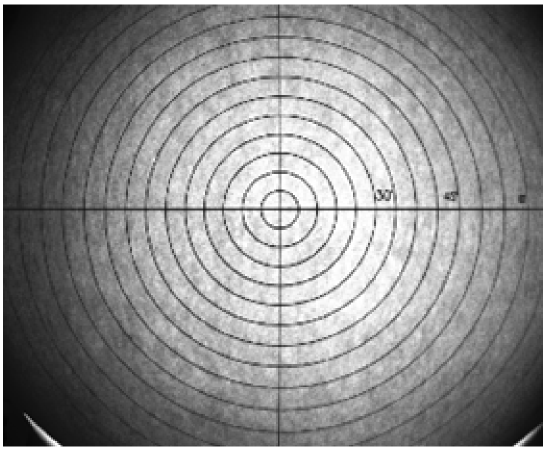

Figure 3.11: Vignetting effects of the CLLS equipped with a fisheye lens.

Vignetting effects had accordingly to be corrected to compensate the luminance loss at the lens's edges. To assess the potential vignetting effects, a measurement was set-up as shown in Figure 3.12 a)-c). The camera was fixed to a rotating tripod and placed on an axis orthogonal to the light source. It was then rotated by using 5° steps both in the horizontal and the vertical directions; snapshots were taken at each position, while maintaining the luminous intensity constant, as shown in Figure 3.12d) [167].

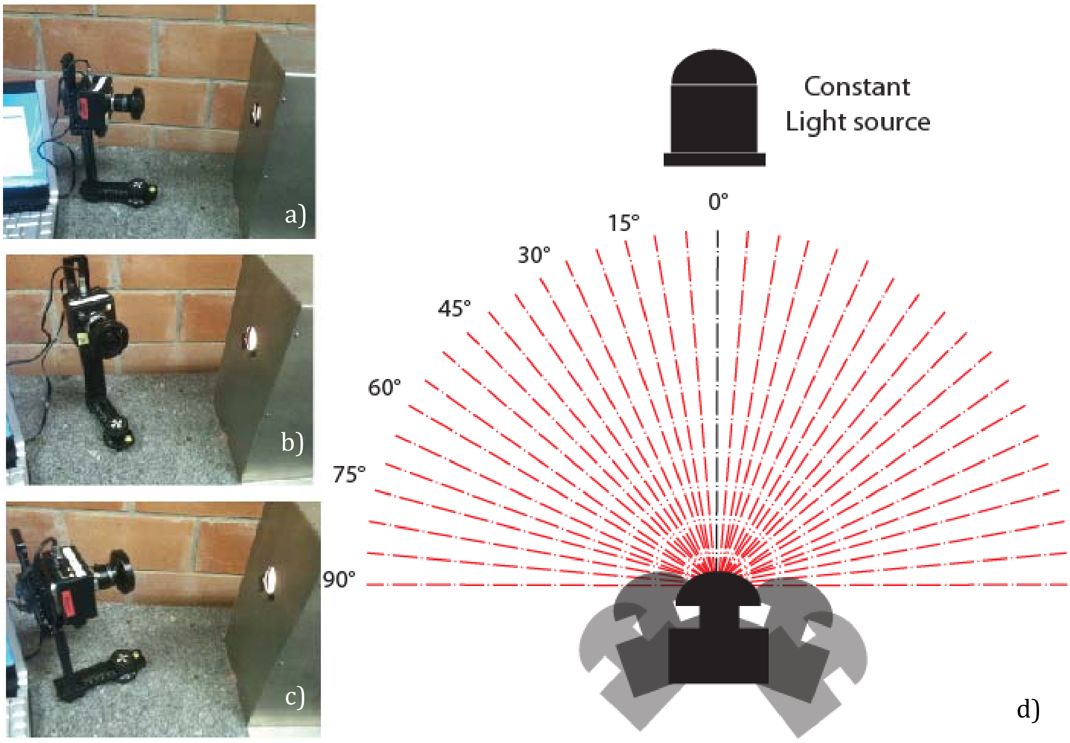

Figure 3.12: Measurement set-up for the vignetting correction; a-c) CLLS located in front of a constant light source, d) the device was rotated in 5° angle steps in both, horizontal and vertical directions in order to take pictures at different angles.

The luminances of the light source at different angles were extracted from the luminance maps generated by the "ImageCAM" software. The monitored luminances of the light source plotted for each angle are illustrated in Figure 3.13; they were then fitted (R^2 = 0.97) with a polynomial function according to Equation 3.7. An inverse equation was then computed (Equation 3.8) and finally implemented in the "ImageCAM" software in order to correct the vignetting effects.

$$y = -2.16 \cdot 10^{-12} \cdot x^5 - 1.47 \cdot 10^{-10} \cdot x^4 + 5.52 \cdot 10^{-9} \cdot x^3 - 2.72 \cdot 10^{-6} \cdot x^2 + 2.66 \cdot 10^{-6} \cdot x + 1.000473 \tag{3.7}$$

$$y = 2.27 \cdot 10^{-12} \cdot x^5 + 1.60 \cdot 10^{-10} \cdot x^4 - 5.91 \cdot 10^{-9} \cdot x^3 + 2.71 \cdot 10^{-6} \cdot x^2 + 2.88 \cdot 10^{-6} \cdot x + 0..9995 \tag{3.8}$$

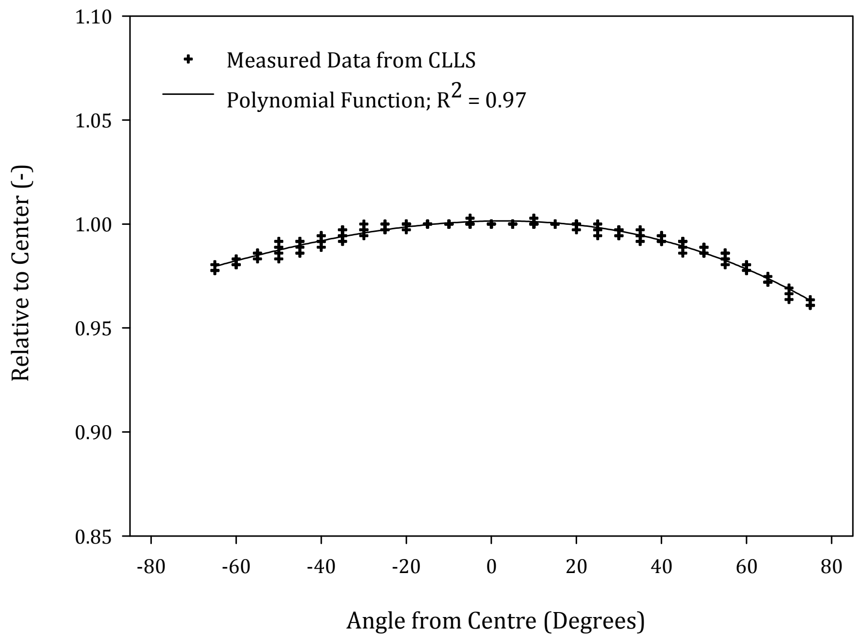

Figure 3.13: Characterization of the vignetting effects of the CLLS fisheye lens. The crosses indicate the measurements for different angles; the solid line shows the fitted polynomial function (according to Equation 3.7); 0= centre.

3.4.3 Experimental validation of CLLS

Luminance mapping

After the overall calibration procedure, luminance mapping of real scenes was performed with the CLLS. The luminance maps were validated by using a calibrated Minolta LS-110 luminance meter (Konica Minolta, Tokyo, Japan). The validated luminance maps were compared with luminance mappings obtained with a Nikon Coolpix 5400 CCD camera, equipped with a FCE-9 fisheye lens. The validation was carried out in an office room at the LESO Solar Experimental building on the EPFL campus (Ecole Polytechnique Fédérale de Lausanne, Switzerland). A standardized colour chart (Macbeth colour checker®, X-Rite, Michigan, USA) as well as different room elements were used as targets for luminance mapping [151]. A set of images was taken: i) under dynamic daylighting conditions and ii) under electric lighting conditions (2 x 36 W fluorescent tubes; 3000K). Fifteen surfaces of different room elements were used beside the standardized colour chart; the locations of the room elements are shown in Figure 3.14.

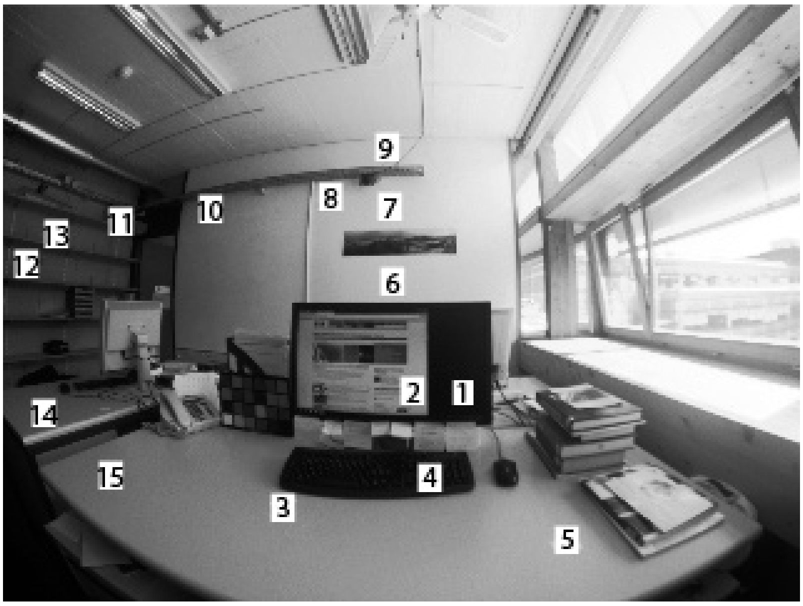

Figure 3.14: Locations of 15 different room elements for the CLLS experimental validation: 1 = PC screen (white), 2 = PC screen (black), 3 = desktop near keyboard, 4 = keyboard, 5 = desktop right side, 6 = lower wall, 7 = middle wall 2, 8 = upper wall, 9 = wall near ceiling, 10 = wall left side, 11 = shelf-top, 12 = shelf-left, 13 = shelf-middle, 14 = desktop of the left side desk, 15 = desktop left side and the colour chart on the desk.

The luminance values of the targets were extracted in two different ways: i) using the implemented "ImageCAM" software for the CLLS images and ii) using the software "Photosphere" [160] for images obtained by the way of HDR techniques (CCD Camera Nikon Coolpix). Both data sets were then compared with the luminance monitored by the luminance meter. The luminance data of the colour chart and the room elements obtained under pure electric lighting conditions (EL) and daylighting conditions (DL), are shown in Figure 3.15. The coefficients of determination (R^2) between the luminance mappings achieved with the CLLS and the 'Classical HDR' imaging technique associated to the luminance meter are shown in Table 3.3 (for different lighting conditions).

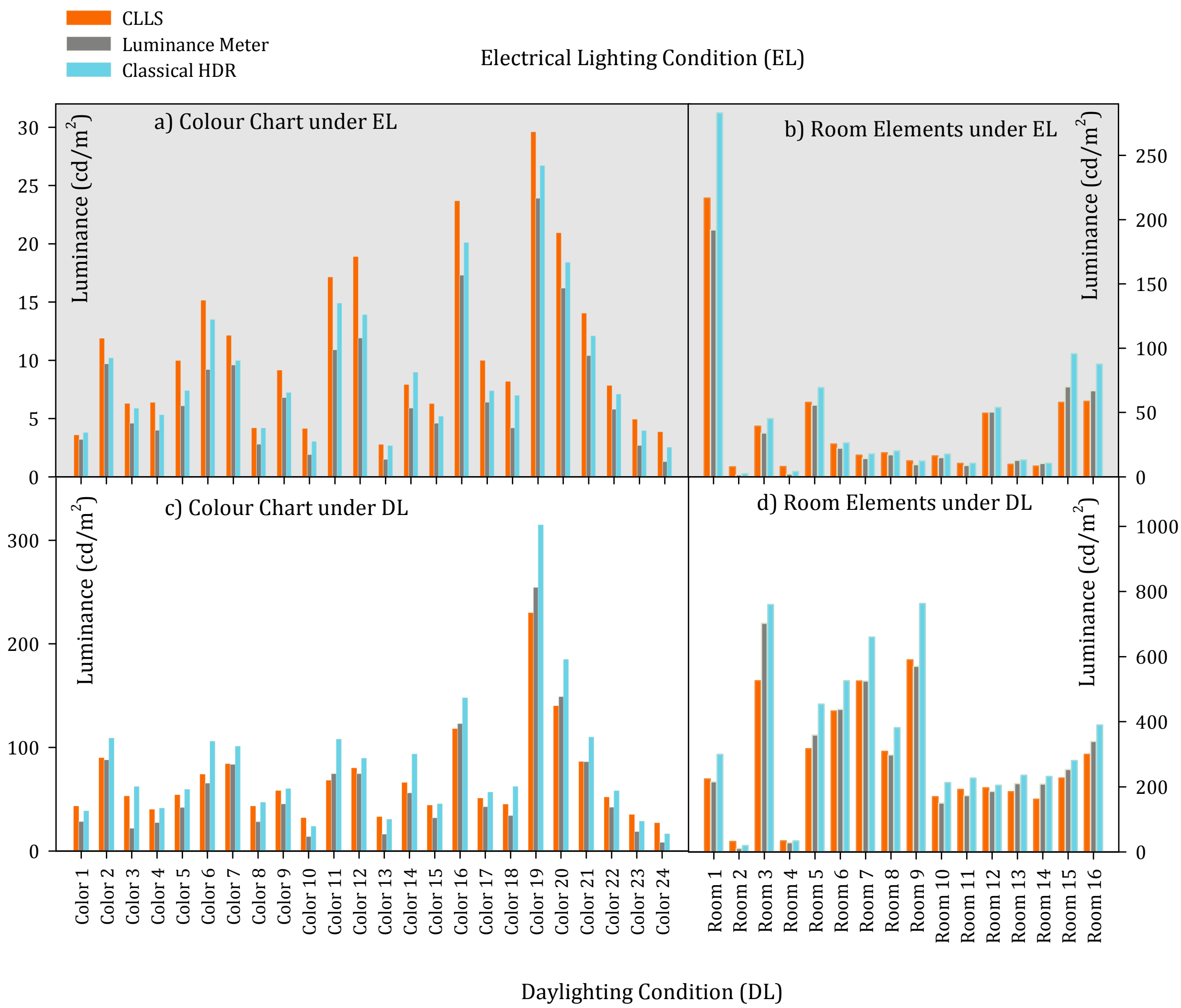

Figure 3.15: Luminance mapping derived from standardized colour charts (Macbeth Colour Checker®) and different office room elements. The data points were extracted from HDR images taken with the CLLS (orange bars) and a Nikon Coolpix CCD camera (HDR imaging technique; blue bars). The reference luminance (from the luminance meter; grey bars) are also shown: a) assessment of the colour chart under electric lighting conditions; b) assessment of the room elements under electric lighting conditions; c) assessment of the colour chart under daylighting conditions; d) assessment of the room elements under daylighting conditions.

Luminance mapping from luminance meter in comparison with		Coefficient determinant (R^2) Colour Chart	Room Elements
EL	CLLS	0.9838	0.9994
	'Classical HDR'	0.9872	0.9990
DL	CLLS	0.9957	0.9803
	'Classical HDR'	0.9953	0.9946

Table 3.3: Coefficient of determination (R^2) of luminance mapping with the CLLS and the 'Classical HDR' technique compared with the luminance meter for different lighting conditions.

Glare risks assessments

A set of HDR images was simultaneously generated using both, the CLLS and the Nikon Coolpix in a LESO daylit office room during three different days. The Evalglare routine [148] was used to compute glare indices for both images. The Daylight Glare Probability (DGP), Daylight Glare Index (DGI) as well as the Unified Glare Rating (UGR) were determined; they are presented in Table 3.4. The values obtained with the 'Classical HDR' technique (CCD camera Nikon Coolpix) were slightly higher than those of the CLLS: the relative differences across three days are equal to 2.9% for the DGP, 12.0% for the DGI and 15.4% for the UGR.

Glare Indices	Day 1		Day 2		Day 3	
	CLLS	'Classical HDR'	CLLS	'Classical HDR'	CLLS	'Classical HDR'
DGP	0.22	0.22	0.23	0.23	0.22	0.24
DGI	12.21	12.74	8.31	10.79	13.3	14.91
UGR	14.38	16.40	11.83	15.21	18.34	21.04

Table 3.4: Glare indices obtained from images at identical office room positions and different days with the CLLS and the Nikon Coolpix CCD camera ('Classical HDR'). DGP = Daylight Glare Probability; DGI = Daylight Glare Index; UGR = Unified Glare Rating [167].

Glare risks assessment for different lighting conditions

In order to confirm the results obtained from HDR images with the CLLS and the Nikon Coolpix for different (day-) lighting conditions, the overall procedure was repeated in a LESO office room. A set of LDR images was taken with the conventional CCD camera (duration of HDR procedure: ~60s) while a sequence of real-time digital images was simultaneously recorded with the CLLS under steady-state electric lighting conditions (for 10s) and daylight conditions (for 60s). Three glare indices (DGP, DGI, UGR) and background luminances were then computed using Evalglare. The values obtained by using the three glare indices, as well as the background luminance are presented in Table 3.5 a) for electrical lighting, and Table 3.5 b) for daylighting.

For electric lighting conditions, the CLLS values obtained after 10s as well as those issued from a conventional 'HDR imaging', were compared with data obtained with the CLLS at 0s. The observed differences are smaller than 3% for both techniques, except for the DGI (5.5% lower than with the CLLS) and the background illuminance (11.8% greater than with the CLLS).

Table 3.5b illustrates the glare indices, as measured with CLLS (three different recording times) and the Nikon Coolpix for varying daylighting conditions. For the latter, no difference was observed for the DGP across the different recording times or between the two techniques. The variations for the DGI, UGR and the background illumination were in the range of 0% to 36.2% (mean ± SD: 11.3 ± 13.2%). The largest difference for background illumination (36.2%) was found for images derived from the 'Classical HDR' technique [167]. The relative differences of the glare indices and the background luminances are illustrated in Figure 3.16 [167].

Lighting Conditions	Glare Indices (Daylight)	DGP	DGI	UGR	Background Luminance
a) Electric Lighting Condition	CLLS <1s	0.18	9.21	11.74	48.0
	CLLS ~10s	0.18	9.17	11.69	48.04
	'Classical HDR' From 14 LDR images during~60s	0.18	8.7	11.34	54.4
b) Dynamic Daylighting Condition	CLLS <1 s	0.23	11.61	15.53	137.2
	CLLS ~10 s	0.23	12.55	16.70	101.62
	CLLS ~20 s	0.23	10.89	15.08	154.96
	CLLS ~30 s	0.23	11.36	15.29	200.61
	CLLS ~40 s	0.23	11.60	15.60	191.82
	CLLS ~50 s	0.23	11.58	15.62	201.58
	CLLS ~60 s	0.23	11.68	15.75	201.65
	'Classical HDR' From 14 LDR images during~60s	0.23	10.79	15.21	215.14

Table 3.5: Glare indices (DGP, DGI and UGR) and background luminance were assessed at the same position for a) steady-state electrical lighting conditions and b) dynamic daylighting conditions with the CLLS (between <1s and 60s), and the Nikon Coolpix ('Classical HDR'; during ~60s).

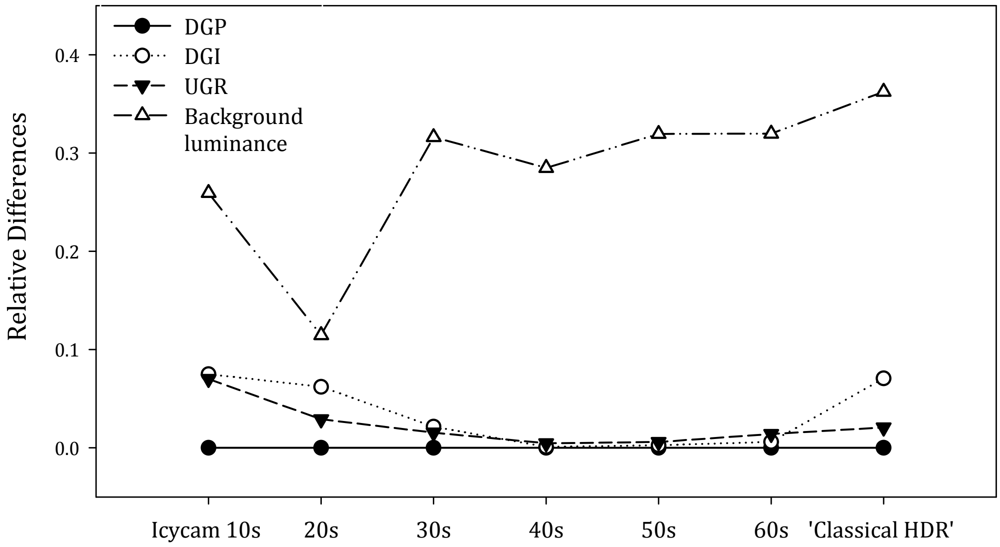

Figure 3.16: Relative differences between the CLLS (from 10s to 60s) and the Nikon Coolpix (after 60s) for daylight conditions regarding glare indices and background luminance at ~0s (with CLLS). Black circles = DGP; white circles = DGI; black triangles = UGR and white triangles=background luminance.

Discussion

The CLLS was successfully calibrated and tested in real scenes. Luminance maps were generated with the CLLS and compared with those obtained by conventional HDR techniques. Different glare risk assessments under steady-state and varying daylighting conditions showed that the new sensor has the advantage to capture HDR images more rapidly, which is of great benefit in dynamic (day-)lighting situations.

The calibration procedure and vignetting corrections resulted in high correlations with the reference devices: the CLLS can thus be reliably used to monitor real scenes. The coefficient of determination (R^2) between luminance maps generated by the CLLS and the conventional CCD camera compared to a point-to-point luminance meter was larger than 0.98. This confirms that both devices (CLLS and conventional HDR imaging) produced similar results, even when tested for different lighting conditions.

Under steady-state electric lighting conditions, the glare indices' differences between both approaches were rather small (less than 6%), except for the background luminance, where the conventional CCD camera assessed higher values. Under varying daylighting conditions, the differences of glare indices between both techniques were larger, compared to electrical lighting conditions; the background luminance varied by a maximum of 36%. The main parameters taken into account for the glare indices calculation, were the background luminance, the luminance of potential glare sources, and the solid angles [45, 153]. The glare indices' differences are most likely due to different background luminance. When the latter varies within short time periods, the glare indices are also modified. Distortions of the two fisheye lenses might also indirectly contribute to the differences of glare indices, since they can impact the solid angles. The differences of DGP between both approaches were smaller than those of the DGI and UGR. This can be due to the vertical illuminance, which is an additional DGP parameter [148]. The vertical illuminances for the DGP calculation were similar whatever technique was used: when they were manually measured during the image capturing, the DGP revealed smaller differences than the other two glare indices [167].

3.4.4 Outlook

The results of the calibration and validation of the CLLS were reported recently in conference proceedings [167]. The main advantage of the CLLS luminance mapping is its high-speed performance. Besides the benefits of time savings, a more accurate assessment is achieved compared to 'Classical HDR' imaging techniques, particularly under dynamic daylighting conditions. The CLLS camera has the potential to become a new and useful application tool for architects, building designers and lighting experts. Dynamic CLLS luminance mapping is thus advantageous, in particular for the assessments under varying lighting conditions such as daylighting. The high speed of the CLLS allows also considering using it in the future as a sky scanner to assess sky luminance distributions even with very dynamic daylight conditions. Since the CLLS is equipped with photopic filters, based on human cone sensitivity, it can also be employed to assess lighting situations in the visible range of wavelengths. An additional potential application of CLLS might be to use a second sensitivity curve which is blue-shifted, also known as C(λ), to monitor biological, non-image forming effects of light; this is considered in the next section.

3.5 Application of CLLS for assessment of non-image forming effects of light

3.5.1 Assessment of non-image forming effects of light

The C(λ) curve or the circadian efficiency functions have been introduced in Section 3.1. As the circadian sensitivity function differs from the V(λ) curve, light monitoring regarding Non-Image Forming (NIF) effects differs from photopic measurements.

In this section, the CLLS is adapted to the C(λ) spectral sensitivity function in order to evaluate light distributions with respect to non-visual functions. Using the C(λ) function, luminous distribution maps of a circadian weighted radiance (L_{ec}) can be created. The CCLS, equipped with customized filters, enables to adapt the camera's spectral sensitivity to the C(λ) function. The distributions of L_{ec} using circadian luminance mapping under electric and daylighting conditions were determined at different times of day.

3.5.2 Calibration procedure

Spectral sensitivity calibration

As described in Section 3.4, the CLLS was calibrated based on the photometric sensitivity function V(λ) and corrected for vignetting effects; in this section, the spectral calibration is described with respect to the circadian sensitivity function C(λ). The experimental set-up is similar to the one used for V(λ) (Figure 3.7). Narrow-bandwidth monochromatic light beams were also used as a reference light source. The CLLS captured digital images of the 470 nm light beams for different intensities. Simultaneously, the emitted radiance was measured with a calibrated spectroradiometer (Specbos 1201, JETI, Jena, Germany). The CLLS provided a single value per pixel on a greyscale (in arbitrary units from 0 to 1024 digits). The greyscale values and the emitted radiance of the spectroradiometer were correlated using a polynomial function given by Equation 3.9. The results showed a high coefficient of determination with $R^2 = 0.9998$.

$$y = 1.25 \cdot 10^{-13} \cdot x^5 - 5.06 \cdot 10^{-11} \cdot x^4 + 1.15 \cdot 10^{-8} \cdot x^3 - 8.62 \cdot 10^{-7} \cdot x^2 + 7.28 \cdot 10^{-5} \cdot +3.16 \cdot 10^{-5} \tag{3.9}$$

The CLLS and the spectroradiometer monitored simultaneously the constant emitted radiance of a light source at different wavelengths in the range of 380 to 780 nm, separated by 5 nm steps. The raw spectral sensitivity of the CLLS, normalized at 470 nm, and the circadian sensitivity curve, as reported from the literature [115], are shown in Figure 3.17a. This sensitivity curve is based on the action spectrum for light-induced melatonin suppression, suggested by Brainard et al. [118] and Thapan et al. [119], as mentioned in Section 3.1 (with a peak sensitivity within 460-480 nm).

Three appropriate filters were identified and combined in order to match the C(λ**)** curve: Scott-S8612, Scott GG420, and Kopp 5030 filters (Schott AG. Mainz, Germany; KoppGlass Inc., PA, USA) were used for that purpose. The optimal thickness of the filters was computed to correct the spectral response and implemented onto the CLLS. To determine the CLLS spectral sensitivity function, the same procedure already used for the V(λ) filter was applied in this case (Figure 3.17b). The corrected sensitivity function is shown in Figure 3.17b and was compared to the circadian sensitivity function suggested by Gall [115]. In order to assess the error between the CLLS relative spectral sensitivity and the C(λ) curve, the CIE standard error f_1' suggested for the V(λ) function (Equation 3.5 [138]) was applied to the C(λ) function as shown by Equation 3.10. A standard error of 10.4% was obtained in this case using the modified formula.

$$f'_1 = 0.93584 \int_0^\infty \left| s(\lambda)_{rel} - C(\lambda) \right| d\lambda \tag{3.10}$$

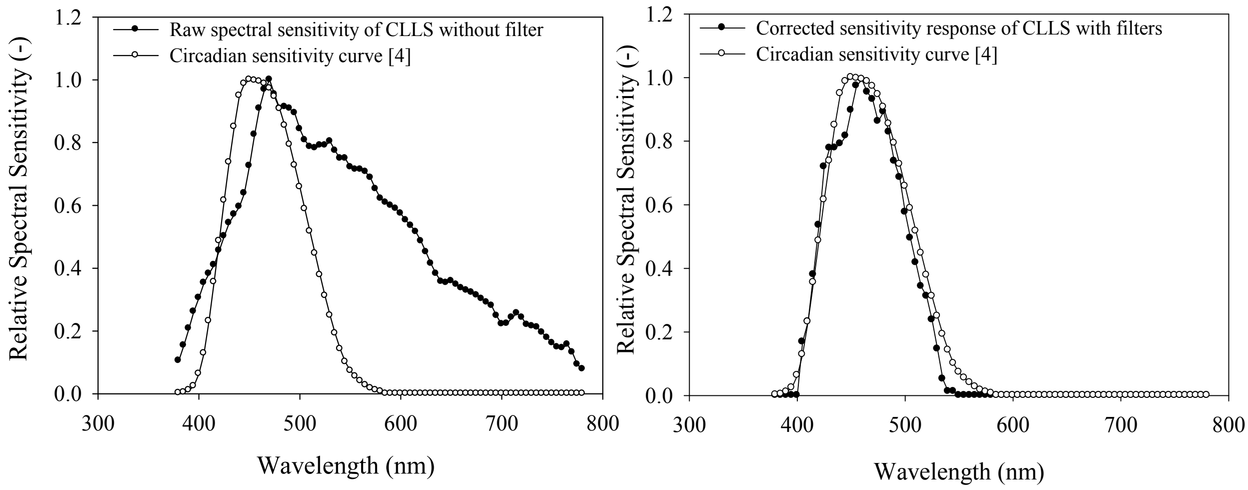

Figure 3.17: Relative spectral sensitivity assessment of the CLLS: a) relative raw spectral sensitivity of the CLLS (normalized data at 470 nm; black circles) and circadian sensitivity function (C(λ) [115]; white circles), b) corrected spectral sensitivity response of the CLLS equipped with filters (black circles) and circadian sensitivity function C (λ) (white circles[115]).

3.5.3 Circadian weighted radiance calibration

To perform the circadian weighted radiance (L_{ec}) calibration, a total of 83 measurements (from 0.04 cd/m2 to 23,871cd/m^2) were made by using simultaneously the CLLS and a calibrated spectroradiometer (Specbos 1201, JETI, Jena, Germany) as the reference sensor. Polychromatic white light from a 1000 W Xenon lamp and from a 1200 W metal halide spotlight were used as reference light sources. The spectroradiometer monitored the L_{ec} values (W/sr·m^2), while the camera provided the associated pixels on a greyscale (in arbitrary units from 0 to 1024 digits). The correlation between the greyscale values and the measured L_{ec} is shown on Figure 3.18. The best fit between the pixel greyscale values and their associated L_{ec} was determined using two different functions:

- For greyscale values lower than 425 digits: the exponential function expressed by Equation 3.11 was employed (R^2=0.97);
- For greyscale values higher than 425 digits: the polynomial function expressed by Equation 3.12 was used (R^2=0.98).

Both functions were finally implemented in the "ImageCAM" software in order generate L_{ec} maps.

$$y = 0.00013e^{0.0176\mathrm{x}} \tag{3.11}$$

$$y = 6.22 \cdot 10^{-15} \cdot x^6 - 7.86 \cdot 10^{-12} \cdot x^5 + 4.13 \cdot 10^{-9} \cdot x^4 - 1.04 \cdot 10^{-6} \cdot x^3 + 1.24 \cdot 10^{-4} \cdot x^2 - 5.56 \cdot 10^{-3} \cdot x + 5.30 \cdot 10^{-2} \tag{3.12}$$

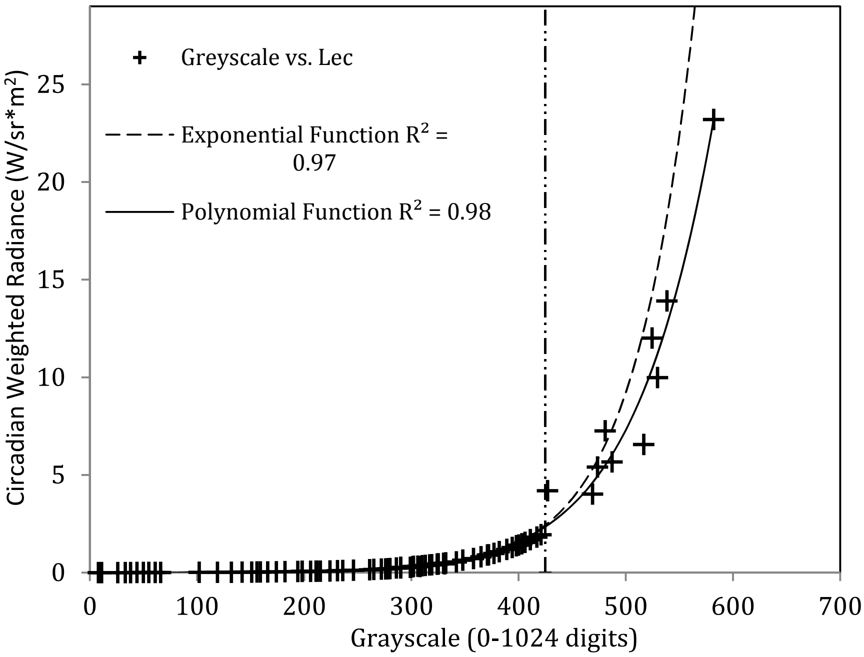

Figure 3.18: Correlations between pixel greyscale values (arbitrary units from 0 to 1024) and associated L_{ec} (W/sr·m²). The black crosses indicate measurements taken with the CLLS and the spectroradiometer; the solid line indicates the fitted exponential function for the greyscale values lower than 425 (R^2=0.97); the dashed line indicates the fitted polynomial function for the greyscale values higher than 425 (R^2=0.98). The vertical dashed and dotted line depicts the border for the two regression functions at a greyscale value of 425 digits.

3.5.4 Experimental validation of the CLLS with the C(λ) filter

Circadian weighted radiance mapping

The CLLS was tested in an office room of the LESO Solar Experimental building located on the EPFL campus (Ecole Polytechnique Fédérale de Lausanne, Switzerland). Twenty different room elements were used as targets for measurements (Figure 3.19). A set of pictures was taken under electric lighting conditions (2 x 36 W fluorescent tubes; 3000K) as well as under daylighting conditions (clear sky). The L_{ec} values of the room elements were simultaneously assessed by the spectroradiometer and by the CLLS. The two data sets were then compared, as shown in Figure 3.20. The coefficients of determination (R^2) between L_{ec} measured with CLLS and the spectroradiometer.

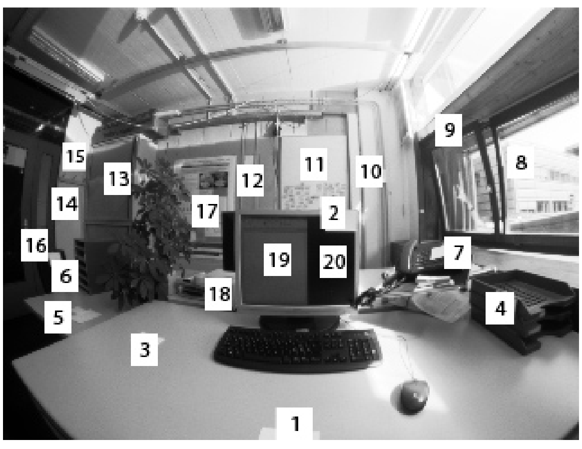

Figure 3.19: Locations of different room elements for the validation of the CLLS. 1=desktop, 2=PC screen, 3=desktop left side, 4=desktop right side, 5= second desk left side, 6 = chair, 7= telephone, 8= window, 9 upper window, 10 = back wall 1, 11 = white board, 12=back wall 2, 13 = closet, 14 = wall left side, 15= door, 16=bottom of the door, 17= poster, 18=behind PC screen, 19=document on PC screen, 20=black wallpaper on PC screen.

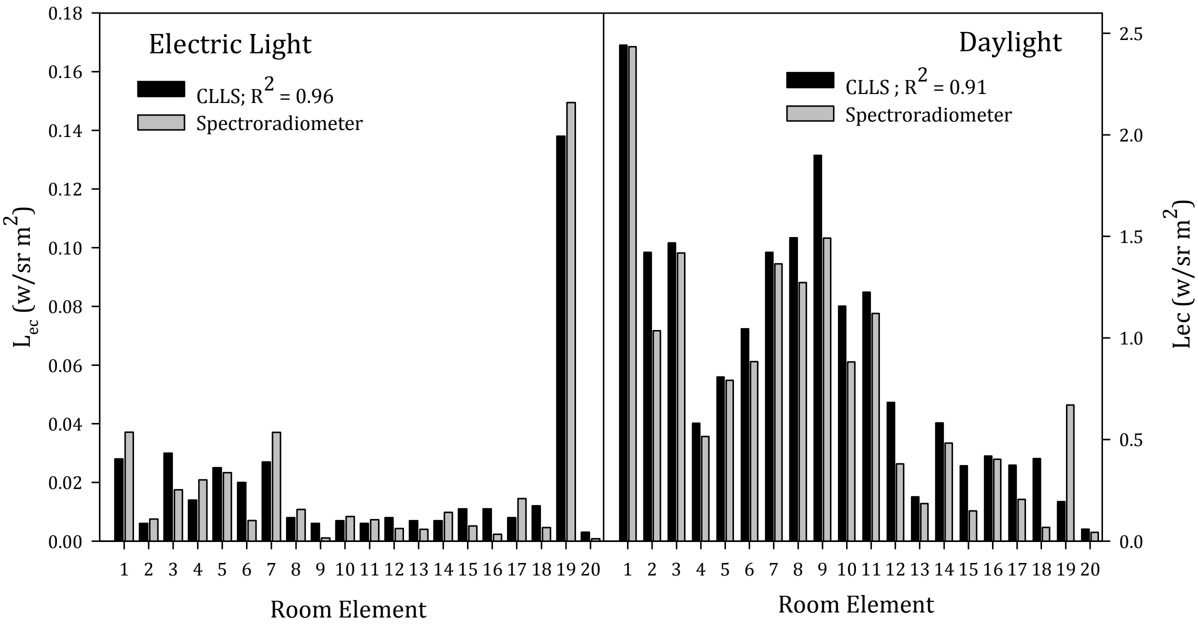

Figure 3.20: L_{ec} value of different office room elements (see Figure 3.19). The data points were obtained from CLLS (black bars) and the reference luminance measurements (spectroradiometer; grey bars). Left: assessment under electric lighting conditions; right: assessments under daylighting conditions.

Comparison of circadian weighted radiance mapping for different daylighting systems and times of day

The CLLS was also employed in two test rooms of the Advanced Windows Testbed facility at the Lawrence Berkeley National Laboratory (LBNL; CA, USA), during a short-term visit and a collaboration between LESO-PB/EPFL and LBNL. Room A is equipped with standard venetian blinds (Figure 3.21a); Room C is equipped with Light Louvers™ (Figure 3.21b). Both complex fenestration systems were located in the upper part of the windows, whereas the lower parts were covered with opaque screens. A set of images was taken with the CLLS at 9AM, 12PM and 3PM. Luminance and L_{ec} were extracted for the same reference points in both rooms (walls, windows, task area and ceiling). The ratio of L_{ec} and luminance (L_{ec}/L) was then determined to assess the circadian efficiency of the light distribution in the room; a higher ratio indicates a larger circadian efficiency. A total of 84 measurements were taken under clear sky conditions; extracted luminance, L_{ec} and ratio on log-transformed drawings were analysed with 2-way repeated analyses of variance (rANOVA) with the factors ‘time’ and ‘room’.

Figure 3.21: a) Room A equipped with standard venetian blinds; b) Room C equipped with Light Louver™

Luminance and L_{ec} in Room A (venetian blinds) were higher than those in Room C (LightLouver™) for all three times of day. For rooms, luminance and L_{ec} were larger at 12PM than at 3PM and lower at 9AM (Figure 3.22 a-b, 'room' x 'time'; $p<0.05$). The ratio of L_{ec}/L was overall larger in Room A than that in Room C ($p<0.05$; main effect of 'room' Figure 3.22 c); the ratio for both rooms was higher at 3PM than at 9AM ($p<0.05$; main effect of 'time'; Figure 3.22c). First comparisons between two different locations in the room (near by the window and deeper in the room), did not reveal any difference in circadian efficiency of light distribution ($p>0.20$).

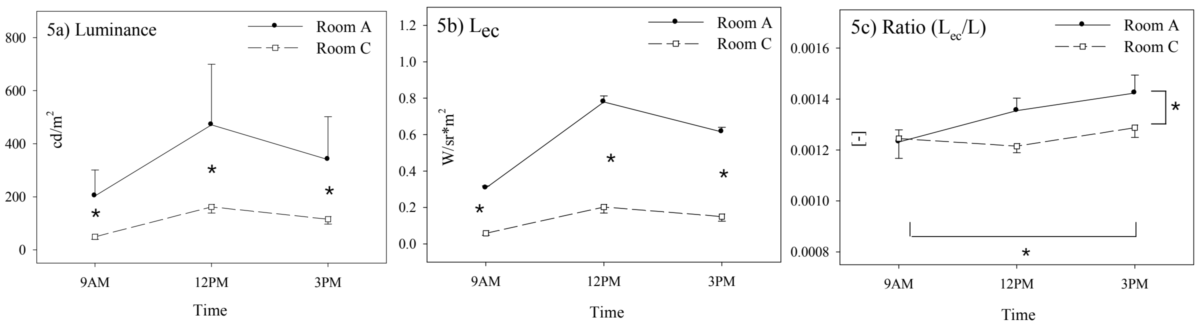

Figure 3.22: a) Luminance, b)L_{ec} and c) ratio (L_{ec} /L) for Room A (black circles) and Room C (white squares) at 9AM, 12PM, and 3PM (mean ± SEM); overall, larger luminance, L_{ec} and ratio in Room A than Room C; larger luminance and L_{ec} at 12PM; larger ratio at 3PM than 9PM (*=$p<0.05$).

Discussion

The CLLS was successfully used in real scenes; it revealed that the correlation of L_{ec} issued from the CLLS and the spectroradiometer was larger for steady-state electric lighting than for daylighting conditions under clear sky.

The room equipped with standard venetian blinds provided larger (photopic) luminance and circadian weighted luminance (L_{ec}) than the room equipped with LightLouver™ throughout the day; larger values were observed at noon. The most likely reason for the dynamics of luminance and L_{ec} is the varying incident angle of sunlight. Interestingly, circadian efficiency was highest at 3PM; one reason for this might be that the different sources of daylight (sun and sky vault) did not only provide different light fluxes, but also induced changes in the spectral composition of daylight.

3.5.5 Outlook

The calibration and the validation of the CLLS were previously published in conference proceedings [171]. Further studies with the CLLS with respect to circadian weighted luminance at different room locations and different times of day are required. One important question remains: What does a higher or lower circadian efficiency mean? Can it be used as a proxy for other biological functions? Future experiments should also test other variables, for example circadian efficiency of light for human alertness, mood and performance.

3.6 Conclusion

Photometric variables, such as luminous intensity and colour appearance of light, have been generally used for characterization of office lighting. However, office lighting criteria for circadian metrics are not established yet. Lighting conditions must be further investigated, especially with respect to NIF effects. Appropriate monitoring and effective devices in circadian metrics must be further developed and become internationally accepted.

An efficient monitoring of luminance distribution, which has an important impact on visual comfort, has yet to be developed. Since the HDR imaging technique has been introduced, luminance distribution can be assessed. However, the assessment of visual discomfort by HDR cannot be performed instantaneously: a set of photographs must be acquired to generate a single HDR image, and capturing several LDR images takes considerable time. The varying luminance of glare sources or background might induce different results, particularly under dynamic daylight conditions.

In the course of this thesis, a Camera-Like Light Sensor (CLLS) has been introduced and calibrated for both photopic and circadian sensitivity functions. The novel device has also been successfully validated, showing that the CLLS considerably facilitates luminance mapping compared to the HDR technique with respect to speed and accuracy. Besides the use for luminance mapping, a circadian weighted radiance map has been introduced for the first time. With the CLLS, the circadian weighted radiance (Lec) can be easily monitored. A first experimental assessment of circadian weighted luminance maps for Complex Fenestration Systems (CFS) was also carried out in this thesis; it reveals different circadian weighted luminous distributions. This particular use of the CLLS is thus innovative for the assessments of light properties with respect to NIF functions within architectural settings. The CLLS has in addition the potential to become a novel and very useful application tool for architects, building designers and lighting experts.

Chapter 4 Non-Image Forming (NIF) biological effects of light

4.1 Principles of NIF effects of light

More than a decade ago, a novel photoreceptor class, the so-called intrinsically photosensitive Retinal Ganglion Cells (ipRGC), was discovered in the mammalian retina [116, 117, 172, 173]. Since then, it has become evident that ocular lighting influences not only the visual system, but also many non-visual effects on a wide range of biological functions, such as physiology, mood and behaviour. These effects are called “Non-Image Forming” (NIF) functions.

Light via the ‘visual path’ is conveyed by rods and cones. Incoming light information (electromagnetic rays) is transformed into electrochemical signals and sent via polysynaptic pathways to the visual cortex. Light via NIF pathways is conveyed by intrinsically photosensitive Retinal Ganglion Cells (ipRGC) via the retinohypothalamic tract to the Suprachiasmatic Nucleus (SCN) and other brain regions, such as the pineal gland which synthesizes melatonin: Figure 4.1 schematically illustrates the pathways of visual and NIF effects in the brain. The IpRGCs are most sensitive in the blue part of light between 460-480 nm [118, 119, 174], when compared to cones (555 nm) and rods (505 nm), as mentioned in Section 3.1. Besides wavelength-dependent differences, other physical properties of the visible electromagnetic spectrum such as luminous intensity, timing, and exposure duration to light also modulate the magnitude of NIF effects. In order to optimize indoor lighting conditions, the fundamentals of the luminous properties that impact NIF effects must be recognized. Environmental light exerts a signal to regulate NIF effects, such as circadian, circannual (seasonal) rhythms [175], the pupil light reflex and hormonal secretions [11-15]. Many of these luminous effects also influence office workers and will be explained in the following section.

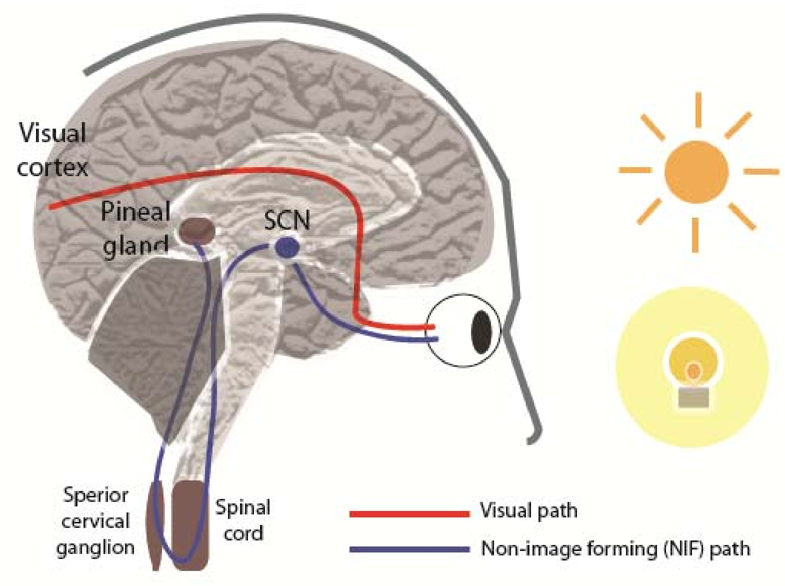

Figure 4.1: Schematic overview of visual (red) and NIF (blue) pathways in the human brain (adapted from [176]).

4.1.1 Circadian rhythms

The circadian system with its master clock in the SCN governs our daily rhythms such as body temperature, sleep and wakefulness, hormonal secretion, and most other physiological functions [9, 15-18]. Endogenous concentration changes of two hormones, melatonin and cortisol are often used as circadian 'phase markers' in humans. Melatonin, also referred to as a "dark hormone", is secreted by the pineal gland during nighttime. It relates to several physiological processes including circadian entrainment, retinal physiology and seasonal reproduction [177]. It reflects the environmental photoperiod via its secretion profile; high levels are secreted during the night, and very low levels or no melatonin is secreted during daytime [178-180]. Since melatonin is important for circadian rhythms, light-induced melatonin suppression can be used to determine the magnitude of these acute light effects [11, 15, 181, 182] Cortisol, also known as "stress hormone" is maximally secreted around habitual wake time and falls to minimum close to habitual bedtime. Morning light exposure, before the daily cortisol peaks, can advance the circadian phase of cortisol rhythms, whilst evening light has no or little significant effect on cortisol secretion [25].

By our daily light and dark cycle, the biological clock in the SCN is synchronised to the external 24-hour cycle. The average period length of human circadian rhythms is approximately 24.2 hours [111]. The circadian phase can be shifted by bright light pulses, depending on their luminous intensity, timing and duration [182-185]. Circadian response curves and circadian action spectra for humans were created [118, 119]. Disruption of this synchrony causes chronic sleep disorders and many other symptoms, also described in combination with jet-lag or shift work disorders [186, 187]. Lack of sufficient light stimuli during daytime and inappropriate light stimuli during nighttime influence circadian disruption, which in turn often leads to the emergence of sleep disorders and other medical or psychiatric diseases [186].

4.1.2 Behavioural effects in office workers

Previous studies reported several NIF effects of light on human physiology and behaviour; the following consequences are some examples of daily (light-dark) environmental effects on office workers and their work performances.

Alertness

Under controlled conditions with scheduled sleep episodes, subjective and objective alertness follows a circadian rhythmicity with a nadir (lowest alertness) at approximately 4h in the morning [188]. The presence of (day-) light intuitively relates to an alert or awake state in humans [189]. The alerting effects of light are determined by many aspects, such as luminous intensity (illuminance), spectral composition of light and exposure duration [189]. The mechanisms for time-of-day dependent effects of light-induced alertness changes during day- and nighttime are still unclear [189, 190]. There have been many studies showing greater alerting responses with bright light exposures at night when compared to dim light conditions [190-194]. Most of these studies concluded that nocturnal light-induced alerting effects were also driven by light-induced melatonin suppression [12, 189, 193]. The explanation is that melatonin can induce sleepiness and therefore its nocturnal suppression by light increases alertness [12, 189, 193]. However, during daytime, melatonin secretion is almost zero, even in very dim light and thus, light-induced alerting effects during daytime cannot be conveyed by melatonin suppression alone [189, 195]. Several studies reported alerting effects by light during daytime as assessed with subjective alertness assessments [190, 196], performance tests (Psychomotor Vigilance Task; PVT) [196], and functional magnetic resonance imaging (fMRI) [197]. One of the studies found that nighttime and daytime bright light similarly reduced sleepiness and fatigue [190]. Two studies analysed the alerting responses assessed by Positron Emission Tomography (PET)[198] during nighttime and by fMRI during daytime [197]. Their results showed that polychromatic light was not only confined to hypothalamic areas including the pineal gland (where melatonin is controlled), but also extended to the modulation of a large-scale network of cortical areas [197, 198]. Recently, Rautkylä et al. [195] suggested that light-induced alertness might involve also other brain mechanisms, which are different from the circadian pathway. Light may connect also to limbic pathways: the limbic system in humans is important for emotional responses [195].

Sleep quality

The 24-h sleep-wake cycle is one of the most important circadian rhythms. Poor sleep can affect physical and mental health [199, 200] and induce work-related problems in cognitive performance [201]. Improving sleep quality increases individual health and well-being including organizational productivity [201].

Polychromatic white or blue-enriched white light exposure during the day increases sleep quality the following night [134, 202]: it is the timing of light exposure which determines the impact on sleep and wakefulness. Bright or blue-enriched light in the evening has a phase delaying effect and thus often results in greater problems to fall asleep [203, 204]; even electronic devices such as laptops influence the following sleep episode [205, 206].

Mood

Several complex aspects including individual physiology and social activities can influence mood [207]. It can vary significantly with circadian phase, but there was no reliable effect of the duration of prior wakefulness [208]. However, a recent study [207] considered data from millions of public online messages across 84 countries for mood expressing words and sentences. The authors found that in the morning, individuals awoke generally in good mood; in the course of the day, mood deteriorated over time. Moreover, the study pointed out seasonal changes of mood: they were dependent on the changes in day-length [207].

Mood can also be influenced by light, depending on illuminance and timing of exposure. Bright light during daytime, particularly daylight or bright light during winter, can improve mood in healthy persons and patients with seasonal affective disorders [209-213]. Many studies investigated the effects of electric lighting (mainly fluorescent light sources) on mood in healthy volunteers during daytime; however, there is no clear conclusion whether different light colours have an effect or not due to a lack of strong evidence, according to the reviews by Veitch and McColl [67, 214]. Interestingly, some studies found that bright light overnight did not appear to have the same effect on mood as during the day [211, 215]. It was noted that the experimental set-up with a controlled routine without sleep during the night might have already a negative effect on mood; thus, short-term light exposures might not be sufficient to change mood in that case [188]. On the other hand, the other field studies reported bright light during nighttime enhanced the mood of night shift workers [216-218], such as night shift nurses [216, 217].

Health and well-being

The short-term effects of light on health and well-being were recently investigated in several studies [17, 18, 46, 79, 219-222]. The terms 'health and well-being' were used for different self-reported questionnaires:

- Subjective perceptions: ocular and eye pain, musculoskeletal symptoms and systemic body symptoms [220], headache [46, 79], dry throat, dry eyes, irritated skin, sniffles [46] and physical clumsiness [221];
- Psychological comfort: tiredness, dullness, irritability [46], satisfaction [17, 222], depression [220], vitality, mental health [79] and mood [222];
- Subjective performance: self-reported productivity [17, 79], trouble with memory [221], subjective daytime alertness [221, 222], job satisfaction, job stress and anxiety[220];
- Sleep quality [46, 79].

Taken together, health and well-being assessments are likely related to (subjective) physical and mental responses to the environment, including lighting conditions. From these studies, several associations of health and well-being with lighting conditions were found; higher correlated colour temperature (CCT) improved well-being [221]. Outside view through windows enhanced well-being which led to better sleep quality [46]. However, no statistically significant differences of well-being were found at a work place for different illuminance conditions (500 lx, 1500lx or

2500 lx) [222] and different light characteristics (dynamic vs. static lighting [79]/ direct or indirect [220]) or different lighting conditions for daytime shifts.

Disorders

The lack of sufficient light during daytime (e.g. in fall/winter) can stimulate the emergence of seasonal affective disorders (SAD) in humans. Rosen et al found that the prevalence of SAD depended on geographical latitude, but not longitude. The global sensitivity score (GSS) was rated higher in increasing latitude north of the equator [223]. Light therapy has been accepted as a treatment for SAD and non-seasonal psychiatric disorders (for a review see Terman et al. 2010 [224]).

4.1.3 Inter-individual differences

To optimize lighting conditions for NIF effects, inter-individual differences such as age, gender and chronotypes should also be taken into account. The term chronotype refers to subjective preferences of early or late (morning type or evening type) habitual sleep/wake time [225]. From these subjective preferences, extreme morning and evening types as well as intermediate chrontoypes can be categorized, based on questionnaires [226]. Other inter-individual differences such as gender and age may interact with a certain chronotype; during life span, the chronotype can even change from a late to an early 'bird' as described by Roenneberg et al. [227]. The change in chronotype starts at the age of 10 year-old, when children become rather evening types until they reach the end of their adolescence. With increasing age, adults change towards earlier chrontoypes [227]. Interestingly, females have a tendency to develop this earlier than males: i.e. women become the 'latest' types on average at the age of 19.5 years (men: 20.9 year-old). By the end of the menopause in women, sex differences in chronotypes seem to disappear [227].

The effects of light on different genders and ages have been also reported. Melatonin suppression was significantly lower in the elderly subjects following exposure to short wavelength (456 nm) light, when compared to the young subjects [228]. This might reflect age-related changes in lens density; however, the differences in gender are still unclear. Some studies found no significant gender difference in melatonin suppression [229, 230], but others showed that females had greater melatonin suppression in response to light exposure than males [231, 232].

4.2 Luminous properties modulating NIF effects in humans

This section describes the different fundamental characteristics of light, which influence different NIF effects.

4.2.1 Illuminance

Light entering the eye is the main stimulus for controlling synchronization of circadian rhythms with the environmental 24-h light-dark cycles [15, 182, 184, 188, 233]; it is therefore evident that for NIF effects, one has to measure illuminance at the human eye in a vertical plane. This diverges from standard measures, where illuminance is indicated in lux (lx) on a horizontal plane. Daytime bright light exposure (~1000 to 7000 lx at the cornea) has been shown to reduce subjective sleepiness [190, 196], induce objective alertness in the electroencephalogram (EEG) [38], and improve task performance, when compared to dim light conditions [196, 197, 234] or lower illuminance (200 lx) [235]. Some studies investigated also the effects of daylight on non-visual functions. Half an hour exposure to a bright daylight flux nearby the windows (1000 lx to over 4000 lx) has been shown to be almost as effective as a short nap in reducing normal post-lunchtime drowsiness in healthy subjects [236]. Another field study showed that exposure to bright light (using a light box inducing approximately 2500 lx at the eye level) enhanced mood and vitality in healthy office workers during winter time in the northern hemisphere [212].

Nocturnal bright light can acutely increase subjective and objective alertness [192-194, 211]. Cajochen et al. [193] reported the dose-response relation of alertness to different intensities of bright light exposures. Comparing alerting responses to polychromatic white light of 9100 lx, the result showed that 50% of the maximal alerting response was reached with less than 100 lx vertical illuminance during night time [193]. The sensitivity to light shows that the illuminance of ambient lighting conditions during early night can increase alertness [193]. It was also shown that high nocturnal illuminance increased performance of complex cognitive tasks and subjective arousal of night shift workers [215]; however, there was no difference of luminous intensity on performance in simple cognitive tasks or mood [215].

4.2.2 Spectral composition of light

In the early 2000's, two independent research teams, Brainard et al. [118] and Thapan et al. [119], found similar action spectrums for hormonal melatonin suppression in humans with a peak in the bluish part of the electromagnetic spectrum of light at 446-477 nm (Figure 4.2); this peak appears to be different from the photopic or scotopic response curves. This work gave further evidence for the existence of a novel non-rod, non-cone photoreceptor pigment, called "melanopsin". Its discovery has been very important for the lighting community since it provided a deeper understanding of the importance of human circadian phototransduction. These findings also fostered novel approaches for light treatment of circadian and affective disorders in clinical and nonclinical settings [237]. Based on the action spectrum of Brainard et al. and Thapan et al. [118, 119], the circadian action function was defined later by Gall et al. and was termed as C(λ) curve [238]. Related circadian action functions are mentioned in Section 3.1.

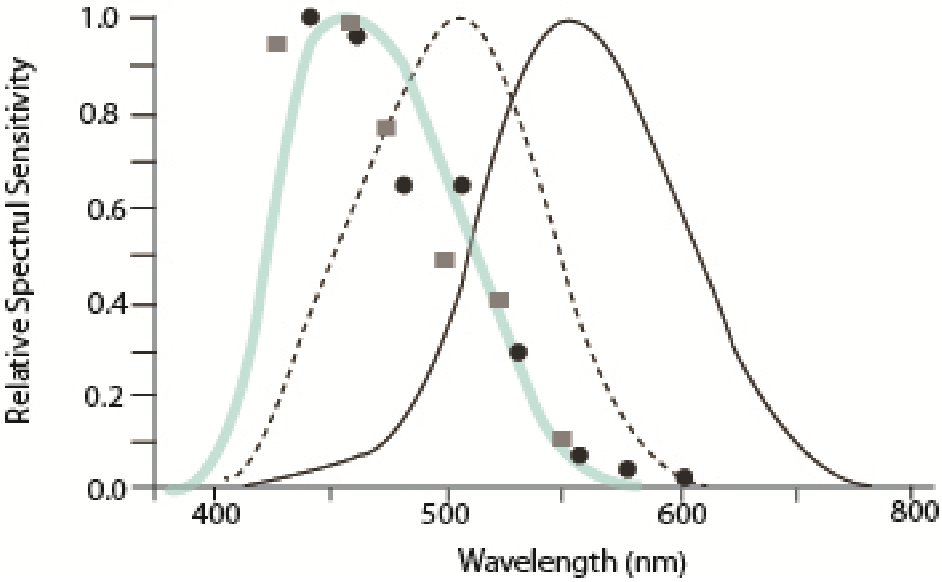

Figure 4.2: Spectral sensitivity curves for melatonin suppression in response to light in humans: grey squares show the spectral sensitivity for melatonin suppression by Brainard et al.[118], black circles show the spectral sensitivity by Thapan et al.[119], light blue line shows circadian sensitivity curves developed by Gall et al. compared with solid line and dotted line indicate specific sensitivity curves of cones (V(λ)) and rods (V'(λ)); adapted from Brainard et al. [118]), Thapan et al. [119] and Gall et al.[238]

Lockley et al. found a greater circadian phase-shifting effect and melatonin suppression with monochromatic blue light (460 nm) than with green light at 555 nm in humans. Exposure to the same wavelengths and luminous intensities resulted in greater effects on subjective alertness, thermoregulation, heart rate and sleep with blue than with green light [12, 239, 240].

The studies mentioned above demonstrate the effects of monochromatic light on NIF effects. Besides luminous intensity, colour appearance of light, such as the correlated color temperature (CCT), the spectral composition of light is also important for office lighting. Higher illuminance stimulated alertness more effectively with 'daylight' (5500K) than with 'warm white' (3000K) polychromatic fluorescent lamps [241]. Another study did not only find stimulating effects on alertness, but also on cognitive performance by applying compact fluorescent lamps at 6500K during two hours. These light sources induced greater melatonin suppression and enhanced subjective alertness, well-being and cognitive performance, when compared to 2500K fluorescent lamps and 3000K incandescent lamps [242]. Two applied office studies showed the influences of blue-enriched polychromatic white light (17000K) on office workers. Viola et al. [202] reported higher subjective alertness and performance, less sleepiness and eye discomfort, when compared to polychromatic white light (4000K) during daytime (over several weeks) [202]. Mills et al. [221] observed the effects from blue enriched polychromatic white light on caller-handlers in the UK, and found an improvement of well-being and work performance [221].

4.2.3 Time of day

Several laboratory–based studies have reported that timing of light exposure is crucial for the human circadian pacemaker [15, 181, 182, 184]: ocular exposure to light stimuli in the morning can significantly advance the circadian phase; on the other hand, light stimuli presented in the evening can delay the circadian phase. Figure 4.3 shows these circadian phase advances and delays on a phase response curve to light stimuli (10'000 lx); phase advances (with the positive values), and delays (with negative values) were plotted relative to the core body temperature minimum [183, 243].

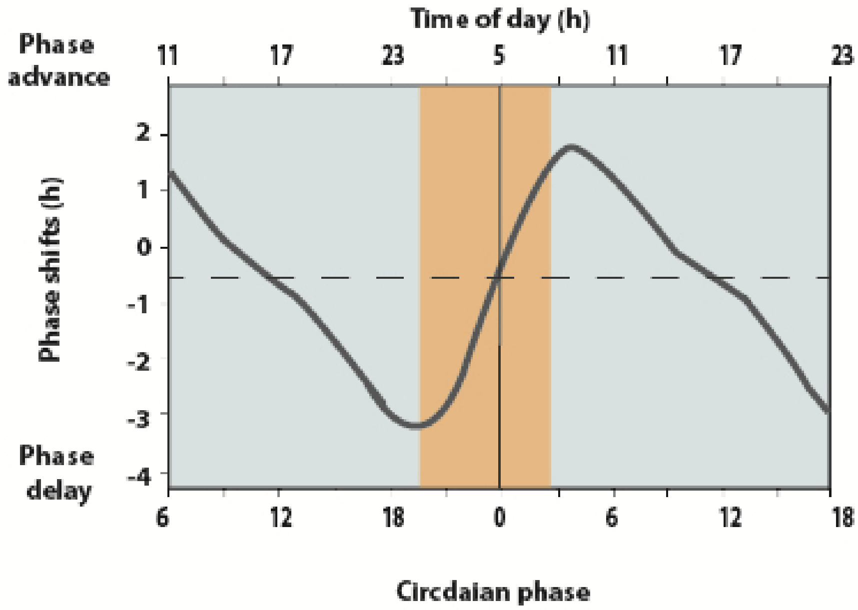

Figure 4.3: Phase response curve to 6.5-hour of bright light with respect to the time of day; phase advances = positive values and delays = negative values; yellow bar = biological night; vertical solid line=core body temperature minimum; the best-fit function to the data plots = solid curve; the assumed average phase-delay drift of the human circadian pacemaker = horizontal dashed line (adapted from [183]).

4.2.4 Issues of NIF effects in architecture and building physics

The discovery of novel photoreceptor cells has also opened the door for innovations in "healthy lighting scenarios" and new approaches in architecture. A field study reported a time-of-day effect of light on hospitalized patients;. Benedetti et al. found that patients with bipolar depression had a shorter hospital stay in eastern rooms (exposed to direct sunlight in the morning), than patients in western rooms (exposed to direct sunlight in the afternoon) [244]. Pechacek et al. [245] presented a simulated annual model of a room in a health care using a computer simulation. They simulated luminance received at the patient's eye (in bed), in order to propose an absolute measure of circadian efficacy [245]. The annual simulation model was performed for different room orientations, window sizes and glazing materials and based on daylight (luminous intensity, spectrum and different times-of-day) received at the patient's eye (in bed), in order to propose an absolute measure of circadian efficacy [245]. Wirz-Justice and

Fournier [246] recently summarized some of the critical questions related to architectural design, lighting and biological aspects in humans [246]. Some draft guidelines were suggested as following:

- Larger luminous intensity is needed for home and workplaces at a certain times of day, different chronotypes and age groups having to be taken into account;
- 'Intelligent' and effective daylighting systems are required, since their higher illuminance, spectrum of light, and timing of light exposure can synchronize our biological clock to the external 24-h hour light/dark;
- Optimized artificial lighting systems, such as spectral composition and dynamic lighting systems, are needed for schools, nursing homes, and offices in order to improve NIF functions and behavior of occupants.
- During nighttime, dark conditions are needed in bedrooms: artificial light sources in public and private spaces should be minimized to avoid 'light pollution' [246].

4.3 Conclusion

Light influences both visual and non-visual biological functions. Office lighting conditions can impact many NIF effects such as alertness, mood and sleep quality in office workers. NIF effects are therefore to be considered for health and well-being, and they also contribute to work performance. The light sensitive photoreceptors (ipRGC) modulate NIF effects; they show a different sensitivity maximum in the visible light spectrum, compared to rods and cones. Certain characteristics of light, such as luminous intensity and spectral composition, which are optimal for NIF, may differ from those for the visual system. Moreover, the timing of light exposure also influences the NIF functions.

It becomes essential to optimize office light-dark conditions with respect to NIF effects; several strategies in lighting practice have been suggested to improve the work environment. Daylight, dynamic lighting and individual lighting control are recommended for health, well-being and productivity [176, 188, 247]; it also will be important to pay attention to inter-individual differences. Currently, we are still in the early state regarding the optimization of lighting conditions; this is also true for NIF effects. Further research in the area of architecture and lighting will be needed in the future for "healthy lighting" at workplaces.

Chapter 5 Experimental studies in office lighting conditions

Most people spend their days at indoor working places where lighting conditions influence visual and non-visual functions [17, 46, 134, 212, 236, 248]. These functions are time-of-day-dependent, vary under different sky conditions and differ between individuals. Office lighting can range from bright daylight to pure electric light in windowless office rooms. Two experimental studies were set-up under realistic day- and artificial office lighting conditions in the LESO Solar Experimental Building on the EPFL Campus (Lausanne, Switzerland). The first experiment aimed to investigate the effects of two different office lighting conditions in the afternoons on subjective alertness, mood, wellbeing and visual comfort in 25 young healthy subjects. In the second experiment, we investigated three different lighting conditions, i.e. very dim, very bright and self-selected lighting on different physiological and subjective variables in 32 young subjects who were extreme morning- or extreme evening types. The following sections describe the methods and results of these two studies.

5.1 Impact of office day- and electric lighting conditions on visual comfort, alertness and mood (Experiment I)

Several studies have investigated visual comfort of daylight in offices, focusing especially on glare sensations [49, 148, 152, 249]. Up to now, only a few studies have investigated the effects of dynamic (day-) lighting conditions in office rooms regarding different visual comfort variables and non-image forming effects over time, and under different sky conditions. The objective of our experiment was to test the acute effects of two different office lighting conditions in the course of the afternoon on visual comfort, alertness, mood and well-being. The full experiment comprised two parts: 1) subjects had to spend the first six hours in the afternoon under two different lighting conditions (daylight and pure electric light) and 2), the two following hours in the evenings were spent under dim light conditions. Some of the preliminary results from the first study part were previously reported [24, 250]. Results from the second part including hormonal responses and cognitive performance under dim light in the evening were published recently [251]. In this section, the results of visual comfort, alertness, mood and well-being during the afternoons will be presented.

5.1.1 Participants and methods

Study participants

Healthy subjects between 20 and 30 years old without any medication or drug abuse were recruited for this study. None of them was an extreme morning or evening type (as assessed by the Horne-Östberg questionnaire). Subjects, who performed night shifts or had travelled across more than two time zones within the last three months, were not considered to participate. A total of 29 subjects were included in the study. Since the visual comfort scale was given only once to the first 4 subjects, these subjects were not included in the analysis. The data of 25 subjects was analysed: 16 men; 9 women; age=23.5 ± 2.3 years (mean ± standard deviation; SD). Seven days prior to the beginning of the study, subjects were asked to maintain a regular sleep duration of approximately 8 hours with bed- and wake-times at a self-selected target time within a range of approximately 30 min. Compliance was controlled by means of a wrist activity monitor (Daqtix® Süttdorf, Germany) and sleep diaries. Wake-time was on average at 7:31AM± 45 min (mean ± SD) and bedtime on average at 11:25PM ± 43 min (mean ± SD). Subjects were also asked to consume alcohol and caffeine with moderation during the seven days before the study, and to completely abstain on study days. All subjects gave their written informed consent during an interview prior to the study. The local ethical commission in Lausanne (Switzerland) approved the study protocol. All study procedures were in agreement with the Declaration of Helsinki.

Room setup

The study was carried out in the meeting room of the Solar Energy and Building Physics Laboratory (LESO-PB) on the EPFL campus. The two lighting conditions are illustrated in Figure 5.1, and summarized in Table 5.1.

Figure 5.1: Two lighting conditions during the study: a) (mainly) daylighting conditions; b) purely electric lighting conditions.

Code	Lighting conditions	Target vertical illuminance	Lighting system	Vertical view from windows
EL	Electric lighting	174 lx	Ceiling light (4000K)	Outside view was completely covered with opaque curtains
DL	Daylighting	1000-2000lx	Daylight + ceiling light	The lower part of the windows was covered with translucent blinds

Table 5.1: Summary of the two lighting conditions during the afternoons

The electric lighting (EL) conditions were set up to mimic a windowless office by covering the openings with opaque curtains which prevented any diffuse daylight and/or sunrays to enter the room. The horizontal illuminance at desk level in the middle of the room was set to 400 lx (corresponding to 174 lx in a vertical plane at the eye level). The daylighting (DL) conditions were set up in the same room by providing daylight through Anidolic Daylighting Systems (ADS) located at upper part of the windows. The ADS re-directs the daylight flux to the ceiling and to the rear of the room [252]. The lower window parts were covered with textile blinds to prevent any outdoor window view. The vertical illuminance (E_v), defined as illuminance on a vertical plane at the subjects' eyes, was aimed to be in the range of 1000 to 2000 lx; the electric lighting was switched on if E_v was below 1000 lx. If the vertical illuminance exceeded this target range and/or direct sunlight entered the room, the upper blinds were partially closed. The vertical illuminance (E_v), the Correlated Colour Temperature (CCT), the Colour Rendering Index (CRI) and the Circadian Weighted Irradiance (E_{ec}) were continuously monitored in 5 min intervals throughout the study. These variables were assessed using a calibrated spectroradiometer (Specbos 1201, JETI, Germany), placed next to the subjects. The light sensor of the spectrometer was at the height of the subject's eye level. Series of snapshots of the scene, reproducing the subjects' view at 12PM, 3PM and 5:30PM, were taken during the experiments. The photos were processed by High Dynamic Range (HDR) procedures (see Chapter 3), to determine the luminous distribution in the room. This part will be discussed in more details in Chapter 6.

Study protocol

The participants spent two consecutive afternoons and early evenings in the test room. They came twice to the laboratory around noon, once for the DL and once for the EL condition (in a balanced cross-over design). During the afternoon hours, they were allowed to read, work or listen to music, but not to perform any computer tasks. Regularly (every 30-60 minutes), subjects had to assess their visual comfort, subjective alertness, mood and well-being. A trained assistant was present in the test room to ensure compliance with the study procedures.

Subjective assessments

During both study days, subjects had to assess visual comfort, subjective alertness, mood and well-being on paper-based questionnaires by the way of a visual analogue scale. They had to indicate their current status between two extremes (for example: extremely sleepy and extremely alert) on a horizontal line (0-100 mm)[253] .

Visual comfort ratings

Two questionnaires were used for visual comfort assessments. In the course of the afternoon, subjects completed each hour seven items of the Visual Comfort Scale (VCS; see Appendix A). The items were extracted from the full Office Lighting Survey (OLS) questionnaire [80, 254]. The seven items where modified to be used on a continuous visual analogue scale. Once towards the end of the afternoon, subjects had to fill in a modified OLS version [250] (10 items; for details see Table 5.3) on continuous visual analogue scales.

Non-visual functions assessments

In the course of the afternoon, subjects assessed every 30 minutes their subjective alertness, mood, physical well-being and relaxation on continuous visual analogue scales (see Appendix A).

Statistics

The software Statistica 6.12 (StatSoft, USA) was used for statistical analyses. The non-visual function assessments were collapsed in hourly bins. Results from subjective ratings were analysed by performing repeated analyses of variance (rANOVA) with the factors 'time', 'condition' (DL, EL), 'gender' and 'order' (begin with EL or DL). Missing data from the subjective questionnaires were linearly interpolated. For post-hoc analysis, the Duncan's multiple range test and t-tests were applied. For correlation analysis, the Pearson's correlation was used. In order to analyse significant changes in the course of the afternoon, subjective assessments at each time point were compared to the beginning of the study by using t-tests with adjusted p-values for multiple comparisons. For p-value adjustments, the False Discovery Rate (FDR) was used [255].

5.1.2 Results

Photometric variables

The vertical illuminance (E_v) during the DL condition was on average 965.8 ± 94.5 lx and 174.3 ± 1.0 lx for the EL condition (mean ± standard error of mean; SEM). All photometric measures (E_v, CCT, CRI and E_{ec}) are summarized in Table 5.2 for both lighting conditions. The EL condition was steady-state, whereas the DL condition was dynamic such that E_v, CCT, CRI as well as E_{ec} varied over time, as shown in Figure 5.2.

Light Properties	Unit	Electrical Light (EL) n = 25 (mean ± SEM)	Daylight (DL) n = 25 (mean ± SEM)
Ev	Lx	174.3 ± 1.0	965.8 ± 94.5
CCT	K	3707.0 ± 5.8	4284.2 ± 44.3
CRI	-	83.4 ± 0.03	89.9 ± 0.6
Eec	W/m2	0.13 ± 0.001	1.9 ±1.0

Table 5.2: Averaged vertical illuminance (Ev; lx); Correlated Color Temperature (CCT; K), Color Rendering Index (CRI; no units) and circadian weighted irradiance (Eec; W/m2) during DL and EL (mean of all hours ± SEM).

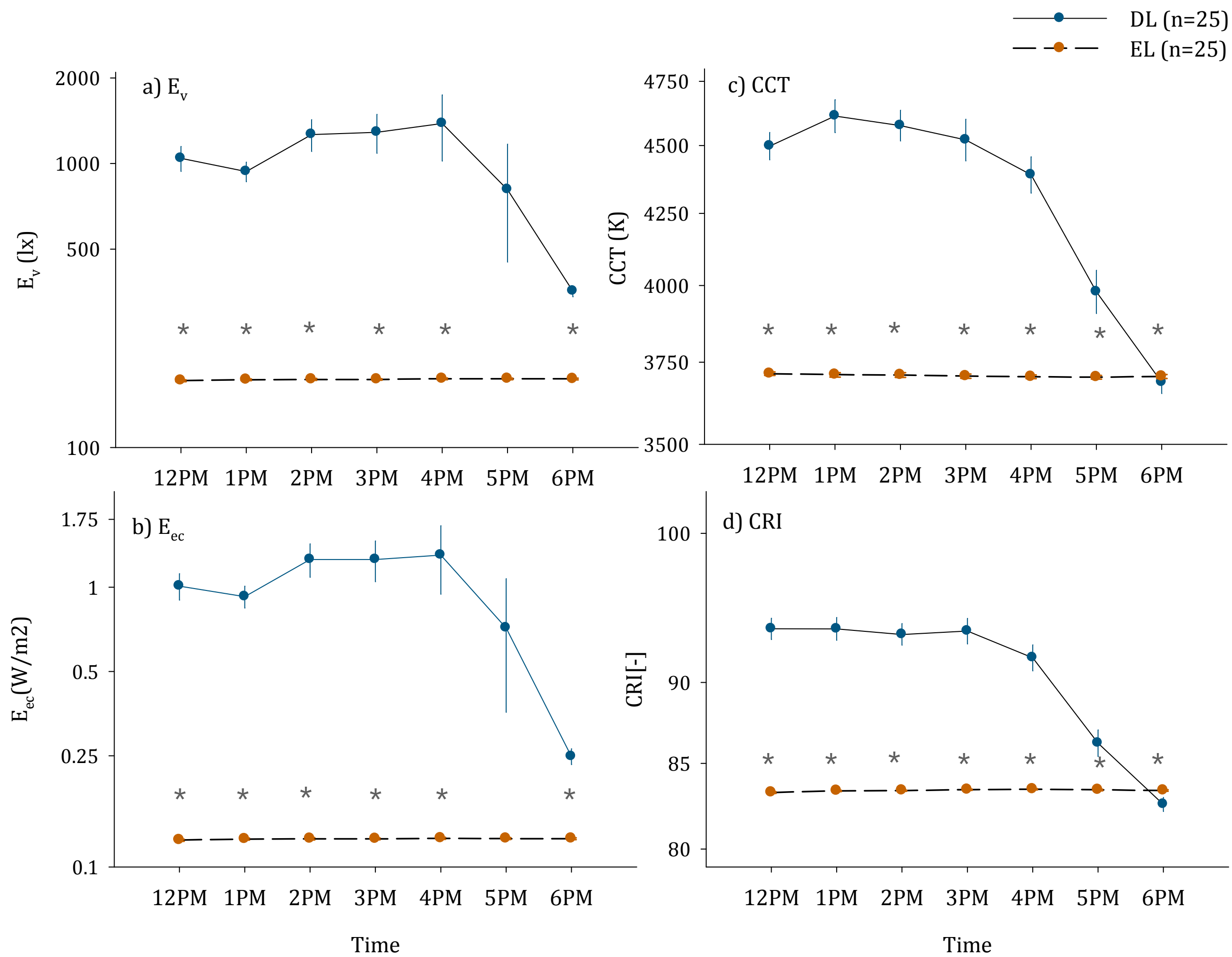

Figure 5.2: Averaged photometric variables in the course of the afternoon (mean ± SEM) a) Vertical illuminance (E_v) on a log scale; b) Circadian weighted irradiance (Eec); c) Correlated Colour Temperature (CCT); d) Colour Rendering Index (CRI); DL condition = blue circles and EL condition =orange circles; * indicates the differences between DL and EL; p<0.05.

The DL conditions between 12PM and 4PM showed significantly higher E_v, CCT, CRI and E_{ec} values, when compared to the EL conditions (t-test; p<0.01; Figure 5.2). Since the study was conducted during fall and winter, all photometric variables under DL conditions were significantly higher between 12PM and 4PM, when compared to those at 6PM (t-test; p<0.01), because of the fading of daylight.

Visual comfort variables

Subjective assessments of visual comfort showed a significantly better visual comfort, greater light preference, lower glare sensation and a larger lighting sufficiency for work under DL than under EL conditions (4-way rANOVA; main effect of 'condition'; $p<0.05$; Figure 5.3). All assessments for light preference, visual comfort and subjective glare ratings were within the range of satisfaction (> 50), for both lighting conditions. Light preference and visual comfort ratings became lower in the course of the afternoon for both lighting conditions (Duncan's multiple range test; $p<0.05$). Subjective glare ratings were significantly higher under EL compared to DL after 2PM, as shown in Figure 5.4 (2-way rANOVA; 'time x condition'; Duncan's multiple range test; $p<0.05$), indicating higher glare perception under EL.

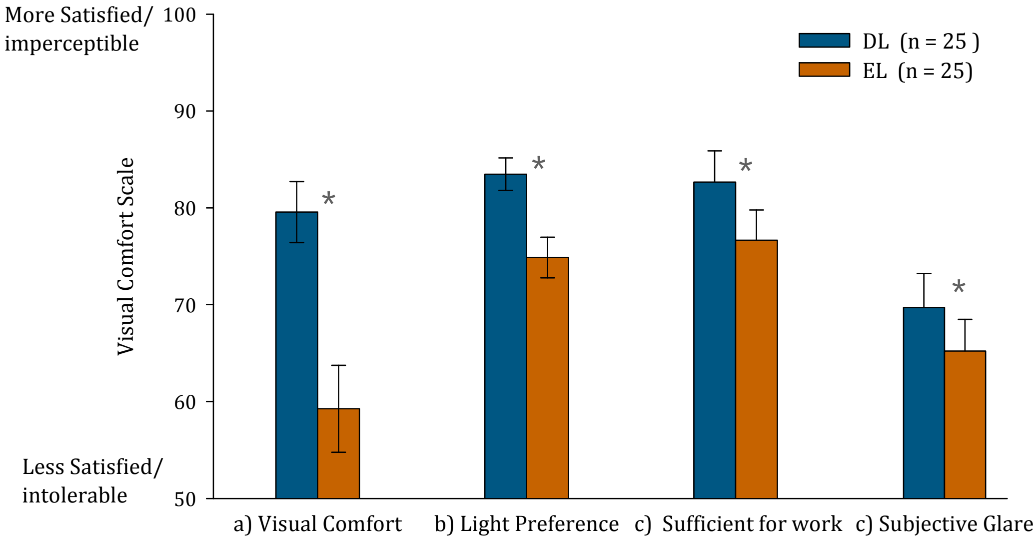

Figure 5.3: Averaged subjective assessments of a) visual comfort; b) light preference; c) subjective glare ratings; and d) sufficiency for work rating; DL = blue bars and EL = orange bars; * = $p<0.05$ (mean ± SEM; n = 25; 0 = not satisfied at all; 100 = extremely satisfied).

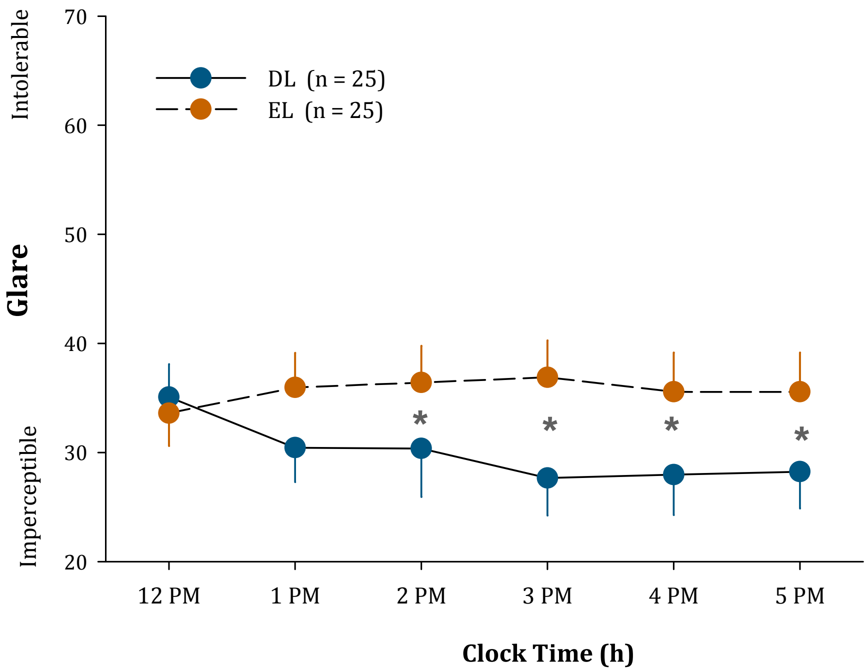

Figure 5.4: Averaged subjective glare assessments per hour; DL = blue circles and EL = orange circles (mean ± SEM); * = significant differences between DL and EL; n = 25.

For the modified version of the entire OLS questionnaire (given once towards the end of the afternoon; Table 5.3). The luminous distribution was rated as being significantly better under DL than under EL conditions: the subjects reported having less reflections, light flickering and shadows ($p<0.05$). Subjects also rated the light appearance to be 'colder' under EL than under DL conditions ($p<0.05$). They found that the lighting under the DL conditions was better than in their existing offices, and they estimated to be able to work for a longer time period under DL than under EL conditions ($p<0.01$). The latter was also dependent on whether the subjects had DL on their first or on their second study day (main effect of 'order'; $p<0.05$). When subjects started their test sessions under DL conditions, they found the lighting under EL conditions less evenly distributed and judged that they would spend less time in the that lighting environment than those who started their session with EL (main effect of 'order'; $p<0.05$).

Non-repeated questionnaire (0 = Yes / 100 = No)	Main effect of									
	condition					order				
	DL		EL		Value	DL/EL		EL/DL		Value
	Mean	SE	Mean	SE	p	Mean	SE	Mean	SE	p
1. The lighting is poorly distributed	90.4	2.2	77.2	5.4	**	74.9	5.4	92.0	2.0	*
2. The lighting causes deep shadows	83.7	3.8	73.2	6.0	*	71.4	5.8	85.0	4.1	-
3. Reflections from the light fixtures hinder my work	77.9	5.4	64.7	6.5	**	72.8	5.3	69.8	6.7	-
4. The ceiling light fixtures are too bright	79.9	3.8	75.2	4.7	-	79.9	3.0	75.4	5.0	-
5. My skin has an unnatural tone under the lighting	71.0	5.9	68.8	5.2	-	63.5	6.1	75.9	4.8	-
6. The lighting flickers throughout the day	88.1	3.6	78.0	5.0	**	78.6	5.1	87.2	3.7	-
7. The colour of the lighting is too “warm”	88.1	2.3	90.4	1.8	-	87.7	2.3	90.7	1.8	-
8. The colour of the lighting is too “cold”	67.9	5.2	46.6	6.3	**	50.1	6.0	63.9	6.0	-
9. How does the lighting of this office compare with the lighting of other offices you have worked in? (1=better…5=worse)	2.4	0.2	3.2	0.2	**	3.0	0.2	2.6	0.2	-
10. For a working day, I imagine that I can work in this light environment for .. hrs	3.4	0.2	2.5	0.2	**	2.6	0.2	3.3	0.2	*

Table 5.3: Averaged ratings for the Office Lighting Survey (OLS) questionnaire under both lighting conditions (DL and EL); mean and standard errors of mean (SEM); * =p<0.05, ** =p<0.01; (3-way rANOVA: ‘condition’, ‘order’ and ’gender’; n=25).

Non-visual functions

There was no significant difference between the two lighting conditions regarding non-visual functions. For both lighting conditions, a significant change over time was observed for subjective alertness, mood, physical wellbeing and relaxation (4-way rANOVA; main effect of ‘time’; p<0.05). They all became worse towards the end of the afternoon. Within each lighting condition, the relative time course of those subjective assessments was further analysed by comparing their changes to the values at noon. After the first hour, subjects reported increased sleepiness and less physical well-being under EL conditions, when compared to the beginning of the study (Figure 5.5; t-test with adjusted p-values by FDR; p<0.023). Under the DL conditions, physical well-being did not significantly change in the course of the afternoon (Figure 5.5a; p>0.05). An earlier decrease of alertness during EL than underDL conditions (Figure 5.5b; t-test with adjusted p-values by FDR; p<0.018) was observed.

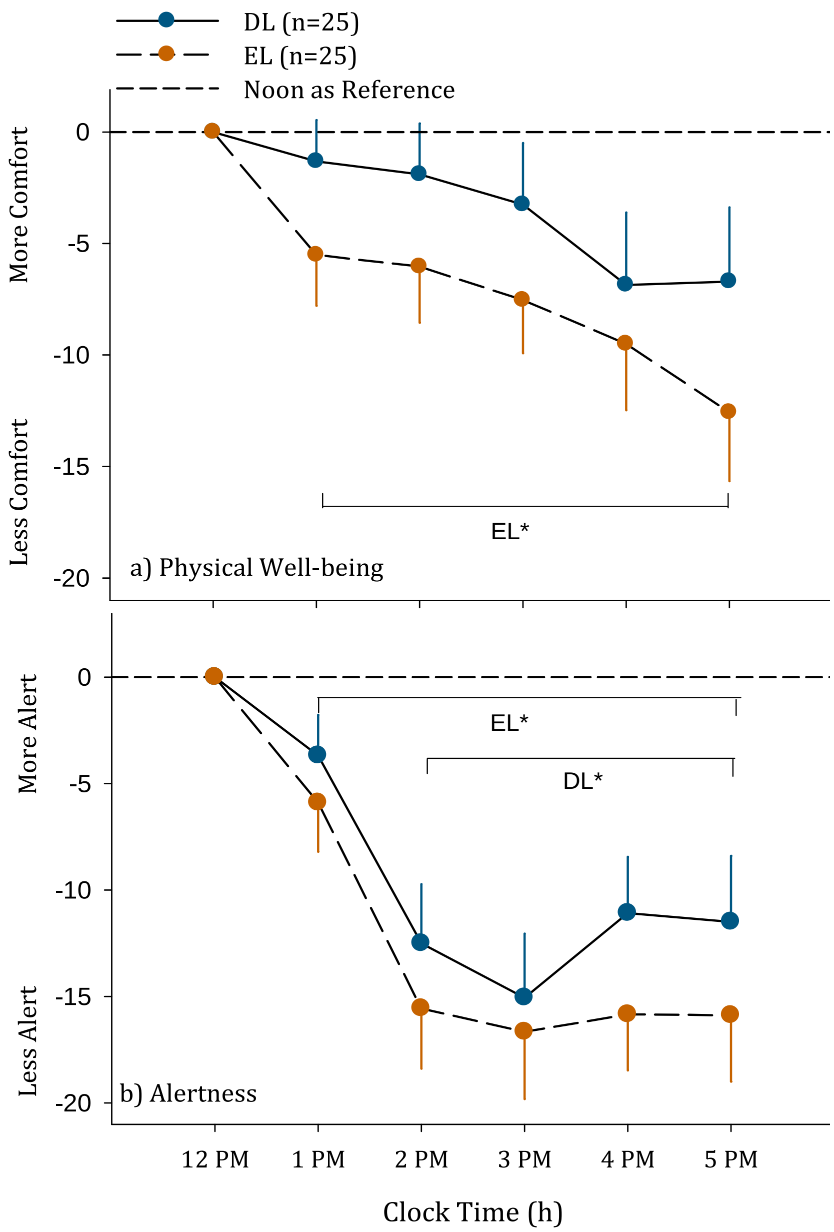

Figure 5.5: Changes in physical well-being (upper Figure) and subjective alertness (lower Figure) during the afternoon, when compared to the beginning of the study (mean ± SEM, n=25); DL = blue circles and EL = orange circles; the horizontal dashed line indicates the value at the beginning of the study; * = significant changes since the beginning of the study (12PM).

Correlation analysis

In order to investigate the relationship between the physical light properties and the responses from subjects, several photometric variables were correlated with subjective assessments. The inter-correlations of different subjective assessments were also analysed. Only statistical significant correlations are shown in Table 5.4 (Pearson's correlation; $p<0.05$).

Correlation between physical light properties and subjective assessments

Table 5.4a) presents the correlation coefficients (r) between some photometric variables and visual comfort variables, including the non-visual functions. Positive correlation coefficients suggest significant intra-individual associations with greater photometric values (E_v, CCT, CRI and E_{ec}) and better visual comfort ratings, as well as greater light preference ($r>0.13$; $p<0.05$). Higher CCT and CRI were associated with better physical well-being and lower glare ratings ($r>0.12$; $p<0.05$). Sunshine duration was also correlated with these variables such that longer daily sunshine hours were related to greater light preference, visual comfort and more relaxation ($r>0.12$; $p<0.05$).

Positively correlation coefficient	Higher light preference	Higher visual comfort	More sufficient to work	More subjective glare	More relaxation	Better phys. well-being	More alert	Better mood
Higher E_v	0.16	0.13	-	-	-	-	-	-
Higher CCT	0.34	0.32	-	-0.19	-	0.13	-	-
Higher CRI	0.33	0.31	-	-0.20	-	0.12	-	-
Higher E_{ec}	0.16	0.13	-	-	-	-	-	-
Longer sunshine duration	0.21	0.18	-	-	0.13	-	-	-
b) Visual comfort variables								
Higher preference	x	0.90	0.42	-	-	0.19	0.28	0.24
Higher visual comfort	0.90	x	0.35	-	-	0.18	0.33	0.19
More sufficient to work	0.42	0.35	x	0.17	0.16	0.11	0.16	-
More subjective glare	0.12	-	0.17	x	0.17	0.16	-	0.24
c) Non-visual functions								
More relaxed	-	-	0.16	0.17	x	0.51	0.18	0.44
Greater physical well-being	0.19	0.18	0.11	0.16	0.51	x	0.50	0.56
More alert	0.28	0.33	0.16	-	0.18	0.50	x	0.47
Better mood	0.24	0.19	-	0.24	0.44	0.56	0.47	x

Table 5.4: Correlation coefficients (Pearson's correlation; r) between visual comfort variables, non-visual functions and light properties; only significant correlations ($p<0.05$) are shown (- = $p>0.05$). Positive correlation coefficients indicate positive correlations of higher visual comfort variables, more relaxation, better physical well-being, higher alertness and better mood with higher Ev, CCT, CRI and longer sunshine duration.

Inter-correlations of subjective assessments

Inter-correlations between visual comfort variables and non-visual functions are summarized in Table 5.4b) and c). Greater light preferences were correlated with a better visual comfort ($r = 0.90$, $p<0.001$); both variables were also positively correlated with greater satisfaction with the lighting for work ($r>0.35$; $p<0.001$). Small, but significant correlations between visual comfort variables and non-visual functions were also found; greater visual comfort and light preference were associated with physical well-being, greater alertness and better mood ($r>0.18$, $p<0.05$).

Greater physical well-being was also associated with more relaxation ($r = 0.51$, $p<0.001$). Both were also related to better mood ($r >0.44$, $p<0.001$) and greater alertness ($r >0.18$, $p<0.001$). More alert subjects were associated with better mood ($r = 0.47$, $p<0.001$).

5.1.3 Discussion

The results showed greater light preference and better visual comfort under DL than under EL conditions, which is in agreement with the current literature [70, 71, 256, 257]. Similarly, glare sensation was better tolerated under DL than under EL conditions, as reported before [23, 45, 258], although the vertical illuminances were larger under DL conditions. A few studies suggested that a pleasant view out of the windows may increase visual comfort and induce lower glare ratings [46, 49]. In our study, any outside view through vertical windows was prevented; hence, view was not the reason for better visual comfort ratings with less glare under DL than under EL conditions in this case. It might not only be the view, but also the photometric properties of daylight *per se* that enhanced visual comfort. We indeed found that higher illuminance, CCT, CRI and E_{ec} as well as longer sunshine durations were correlated with higher light preference and better visual comfort.

Light preference and visual comfort decreased over time, as also shown in a previous report [17], but subjective glare ratings remained constant for both lighting conditions in the course of the afternoon. This implied that lower visual comfort was not always induced by higher discomfort glare ratings.

Non-visual functions, such as relaxation, physical well-being, subjective alertness and mood do not show any significant differences between the two lighting conditions. However, physical well-being and subjective alertness decreased significantly earlier under EL than under DL conditions. This is in agreement with a previous report, showing that sleepiness was reduced after exposure to bright daylight nearby windows for half an hour in the afternoon [236]. Other reports showed that higher light intensity during daytime led to greater alertness and thus served as a countermeasure to an increase of sleepiness during the day [190, 196]. Conversely, mood assessments decreased over time for both lighting conditions, but there was no significant difference between them. There was no correlation between any photometric properties of light and either mood or alertness. The lack of relationship between the two might also be a consequence of the chosen illuminance constraints of the DL condition (i.e. to be between 1000 and 2000 lx).

It must be noted that under DL conditions most of the disability glare was prevented by the use of textile blinds. That might also be the reason of the lower subjective glare ratings found under DL conditions and needs to be considered in a real office setting. Further studies are required to better understand the impact of office lighting by the way of a larger sample size and various light settings. It is also necessary to investigate longer time-dependent light effects during day-time.

Our second experiment focused on inter-individual differences. We included extreme morning and evening types to assess potentially different subjective light 'needs' during working hours.

5.2 Impact of different lighting conditions on visual comfort, discomfort glare, alertness mood and well-being in extreme chronotypes (Experiment II)

As described earlier in this thesis (Section 4.1), light influences several non-image forming effects, such as the entrainment of the internal circadian clock to the external 24 hours of a day. There are large inter-individual differences in habitual daily light exposure times among the general population. These differences are also known from different chronotypes (i.e. morning and evening types). Extreme chronotypes are healthy persons with strong subjective preferences to get up very early and to go to bed very early (morning types), or to get up very late and to go to bed very late (evening types) [225]. Roenneberg et al. [225] reported the associations of longer exposure to bright light in the morning with more advanced sleep periods in humans under daily life situations. Their results suggest that in addition to genetic and behavioural factors, daily light exposures might consolidate the existence of different chronotypes [225]. Morning types showed a longer and more intense habitual exposure to bright light during the day than evening types [225, 259, 260]. The greater daytime light exposure went along with earlier circadian phases. Conversely, the shorter habitual exposures to bright light observed in evening types may contribute to their later circadian phases [259, 261]. A significant positive correlation was found between nocturnal light levels (measured by questionnaires) in adolescents' who are later chronotypes [262]. Vollmer et al. [262] showed that the use of electronic screen media (computer screen or television) at night time is an influential determinant of eveningness. Adolescents living in bright illuminated urban areas showed a stronger eveningness preference than those who are living in darker rural environments [262].

Since light intensity and time-of-day-dependent light exposure modulate circadian phases of physiology and behaviour, extreme morning and evening types are known to be exposed to natural light at different *internal* circadian phases. This may lead to different light effects on visual and non-visual functions. The second experiment was aiming to test the impact of light on subjective and objective visual and non-visual functions, including cognitive performance in young adults, who are extreme chronotypes. Some of the (preliminary) results were previously presented at conferences [263-266]. Some of the data analyses, such as cognitive performance and hormonal analyses are still ongoing. In this section, the impact of light on visual comfort and subjective alertness, mood and well-being in extreme morning and evening types are presented.

5.2.1 Subjects and methods

Study participants

Extreme morning types (MT) and evening types (ET) were recruited by flyers at the University of Lausanne and EPFL (Switzerland). They were selected based on their extreme subjective sleep-wake preferences, as identified by two validated questionnaires: the Horne-Östberg questionnaire [226] and the Munich chronotype questionnaire (MCTQ,[225]). Only healthy subjects being either extreme MT or ET between 20 and 30 years old were included in the study. Except for the chronotype criteria, the inclusion criteria were the same as in Experiment I (Section 5.1.1). A total of 16 MT and 16 ET subjects completed the study (14 men; 18 women; age=22.7 ± 3.5 years; mean ± SD). Seven days prior to the beginning of the latter, subjects were asked to maintain a regular sleep-wake cycle of approximately eight hours each at a self-selected habitual bed and wake-time within a range of approximately 30 min. Compliance was checked by means of a wrist activity monitor (Daqtix® Süttdorf, Germany) and sleep logs. Subjects were also asked to only moderately consume alcohol and caffeine during seven days before the study, and to completely abstain on study days. All subjects gave their written informed consent during a prior interview. The study protocol was approved by the local ethical commission in Lausanne (Switzerland). All procedures were in agreement with the Declaration of Helsinki.

Study protocol

The subjects had to participate in three study sessions. Each of them was scheduled to begin one hour after the habitual wake-time and lasted for 16 hours. The study times and corresponding wake-time/bedtime are summarized on Table 5.5; only one subject was present in each study session. During the study sessions, subjects remained seated in the test room; they were allowed to read, work or listen to music (including one hour of scheduled computer work). A trained assistant stayed with them throughout the study.

Subjects	MT Clock time (mean ± SD)	ET Clock time (mean ± SD)
Wake-time	06:19 ± 0:36	10:18 ± 0:15
Bedtime	22:13 ± 0:42	02:10 ± 0:57
Study begin	07:15 ± 0:34	11:14 ± 1:01
Study end	23:15 ± 0:34	03:14 ± 1:01

Table 5.5: Averaged habitual wake- and bedtimes, study begin and end times (mean± SD) of extreme morning types (MT; N=16) and extreme evening types (ET; N=16).

Room set-up and lighting conditions

The study was performed in the test room of the Solar Energy and Building Physics Laboratory at EPFL, as described in Section 5.1.1. For the three sessions, all subjects underwent three different lighting conditions:

I. Dim light (DIM)

II. Constant bright light (BL)

III. Self-selected lighting (SSL) depending on the subject's choice

To prevent any outside view, all lighting conditions did not allow a view out through the lower windows part. The criteria for the three lighting conditions are summarized on Table 5.6.

Code	Lighting conditions	Vertical illuminance	Daylight	Artificial lighting	Vertical view through windows
DIM	Dim light	< 5 lx	no	yes	no
BL	Bright light	~1000 lx	yes	yes	no
SSL	Self-selected light	Depending on subjects' choices	available	available	no

Table 5.6: Criteria for the three different lighting conditions (DIM, BL and SSL). Set-points of vertical illuminance values were targeted at the subjects' eye level.

For DIM and BL conditions, vertical illuminance was below 5 lx and at approx. 1000 lx, respectively. The study assistant was responsible for the lighting control throughout these two lighting conditions. For the BL condition, there was mainly daylight, which was complemented with electrical light, if the illuminance threshold dropped below 1000 lx. During SSL conditions, the subjects were asked hourly to choose between daylighting and / or electrical lighting; these choices, illustrated in Figure 5.6, comprised:

1) Daylighting conditions:

The daylight flux entered the room via windows equipped with Anidolic Daylighting Systems (as described in Section 5.1.1), located at the upper part of the windows. The façade was equipped with:

a) External blinds: translucent blinds located in front of the lower vertical window were fully lowered in order to prevent any outside view; the upper parts of the blinds were controllable by the subjects.

b) Internal curtain: opaque curtains were available to close all windows in order to use electrical light only (subjects were not allowed to be in complete darkness).

c) Internal californian blinds: movable blinds, installed on the upper part of the window could be used to control the daylight flux (in front of the Anidolic Daylighting System).

2) Artificial lighting conditions:

a) Ceiling mounted luminaries (fluorescent tubes; CCT 4000K, E_v 16- 1280 lx)

b) Indirect light standing lamp (fluorescent tubes; CCT 3000K; E_v 1.1- 52.5 lx)

c) Desk lamp (incandescent light source; E_v 95- 1425 lx)

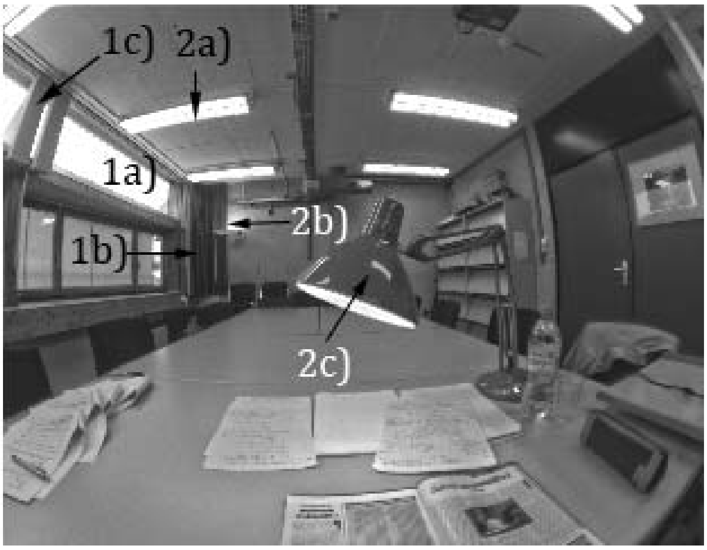

Figure 5.6: Available day- and electric lighting systems to regulate the lighting in the SSL condition: 1a) external blinds; 1b) internal curtains; 1c) Californian blinds; 2a) ceiling light; 2b) indirect light from a standing lamp; 2c) desk lamp.

Vertical illuminance at the subject eyes' level was continuously monitored during the study sessions using a spectroradiometer (Specbos 1201, JETI, Jena, Germany). The study always started with the DIM condition, followed by either the BL or SSL conditions in a balanced cross-over order for both chronotypes. Visual comfort variables were assessed hourly; subjective alertness, mood, physical wellbeing and relaxation were assessed every 30 minutes (see below). Images of the scene mimicking the subjects' view were recorded hourly during the study under BL and SSL conditions using the Camera-Like Light Sensor (CLLS), as described in Chapter 3. The hourly luminous distribution of the scenes was determined; they are discussed in Chapter 6.

Subjective assessments

During the three study sessions, subjects had to assess visual comfort, subjective alertness, mood and well-being on paper-based questionnaires using a visual analogue scale. This required to mark their choice between two extremes (e.g. extremely sleepy and extremely alert) on a horizontal line (0-100 mm)[253] .

Visual comfort variables

This study had slightly different visual comfort assessments, when compared to the first experiment (Section 5.1.1). In the current experiment, subjects assessed each hour 11 items on the Visual Comfort Scale (VCS), which were extracted from the larger Office Lighting Survey (OLS) [80, 254]. The eleven items were modified in order to be used on a continuous visual analogue scale (see Appendix A for details).

Non-visual functions assessments

As in the first experiment (reported in Section 5.1.1), subjects expressed every 30 minutes their subjective alertness, mood, physical well-being and relaxation on a visual analogue scale (see Appendix A).

Statistical analysis

The Statistica 6.12 (StatSoft, USA) software was used to carry out the statistical analyses. The subjective assessments were averaged per hour. Missing data from subjective questionnaires were linearly interpolated. Data from subjective ratings were analyzed first by performing repeated analyses of variance (rANOVA) with the factors: 'time' (hours 1-16 after habitual wake-time), 'condition' (DIM, BL and SSL), 'chronotypes' (MT, ET), 'gender' and 'order' (begin with BL or SSL). In a next step, subjective assessments were analyzed separately for each condition (BL or SSL) in order to investigate the effects of different sky patterns, such as overcast, intermediate and clear sky, at different times (2-way rANOVA; 'weather' x 'time'; for determination of the sky conditions see Chapter 5.2.2). For post-hoc analysis, the Duncan's multiple range test was applied and Pearson's' correlation was used for the correlation analysis.

5.2.2 Results

Photometric variables

The vertical illuminance (E_v), CCT, CRI as well as the circadian weighted irradiance (E_{ec}) were monitored during 16 hours under the three different lighting conditions (DIM, BL and SSL). The vertical illuminance under BL conditions was constant at 1031 ± 64 lux (mean ± SD), while it varied under SSL (714 ± 958; mean ± SD). The averaged photometric variables under different lighting conditions are summarized for all subjects in Table 5.7.

Lighting conditions	E_v (lx) (mean ± SD)	CCT (K) (mean ± SD)	CRI (-) (mean ± SD)	E_{ec} (W/m^2) (mean ± SD)
DIM	3.07±0.4	3115±270	85.8±1.0	0.002±0.0004
BL	1031±64	4120±535	85.7±6.1	0.83 ± 0.18
SSL	714±958	4332±989	90.0±6.2	0.67±0.89

Table 5.7: Averaged vertical illuminance (Ev), CCT, CRI, and Eec (mean ± SD) for DIM, BL, SSL conditions (N=32).

Since daylight is dynamic, the light properties changed over time under SSL and BL conditions (Figure 5.7). Vertical illuminance (E_v) and E_{ec} were on average significantly higher under BL than under SSL conditions (average from 16 hours). The CCT and CRI were significantly higher under SSL than under BL conditions (2-way rANOVA; $p<0.05$).

In order to investigate the differences of lighting environments between the two chronotypes, BL and SSL conditions were analysed separately. There were significant interactions between the factors 'time' and 'chronotype' for all photometric variables, except for illuminance under the BL condition (2-way rANOVA; $p<0.05$ Figure 5.7). Under BL conditions, ET had *highe*r CCT, CRI and E_{ec} than MT in the first 2-3 hours after habitual wake time. These values were *lower* from 5 to 11 hours in ET than MT (Figure 5.7c, e, g). The differences between chronotypes were similar under SSL conditions except for the CCT, where the first 2-3 hours were not statistically different between MT and ET. (Figure 5.7 b, d, f, h).

For further analysis of SSL and BL conditions, the weather status was characterized by three different sky conditions (clear, intermediate and overcast sky), according to the Swiss Norm 150 911 [267]. The meteorological data were issued from the local weather station (Meteosuisse, Pully, VD, Switzerland) [268]. A clear sky refers to a 0%-25% of cloud covering during the days of the study; an overcast sky reflects to 75% -100% of cloud covering. A sky with a cloud covering between 25% and 75% is considered as an intermediate sky. The averaged E_v, CCT, CRI and E_{ec} values for different sky conditions are shown in Table 5.8. For BL, the CCT, CRI and $E_{ec,}$ where significantly lower for overcast skies, when compared to the other two sky conditions. For SSL conditions, there was higher E_v and E_{ec} for clear skies than for overcast skies, and higher CCT and E_{ec} for intermediate skies than for overcast skies (Table 5.8).

Lighting conditions	Sky conditions	N	E_v (lx) (mean ± SD)	CCT (K) (mean ± SD)	CRI (-) (mean ± SD)	E_{ec} (W/m^2) (mean ± SD)
BL	Overcast	10	1039 ± 56	3879 ±191$^{+\#}$	83.1 ± 3.3$^{+\#}$	0.76±0.09$^{+\#}$
	Intermediate	11	1039 ± 90	4177±542	86.3 ± 6.2	0.86 ±0.2
	Clear	11	1020 ± 64	4276 ±652	87.4 ± 7.2	0.87 ±0.2
SSL	Overcast	13	457±303$^{\#}$	4064 ±765^{+}	88.9± 5.5	0.39 ±0.31$^{+\#}$
	Intermediate	6	771 ±618	4812 ±1166	90.9±7.2	0.88 ±1.4
	Clear	13	934 ±1349	4377 ±1011	90.6 ± 6.1	0.89 ±1.2

Table 5.8: Averaged vertical illuminance (Ev), CCT, CRI, and Eec (mean ± SD) under DIM, BL, SSL conditions with different sky conditions (overcast, intermediate and clear sky). N= number of subjects in the respective condition; + = significant differences between intermediate and overcast sky (p<0.05); # = significant difference between clear and overcast sky (p<0.05).

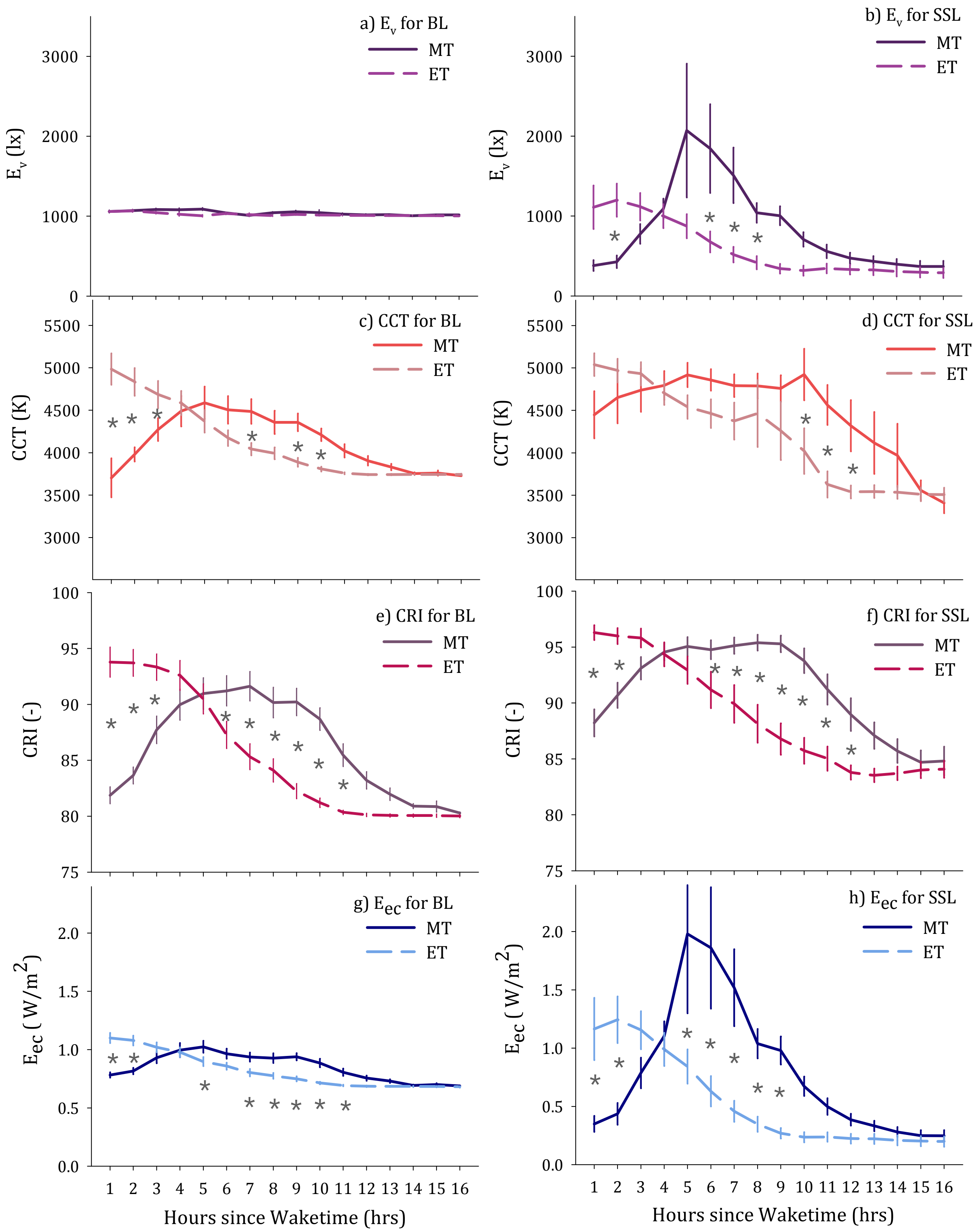

Figure 5.7: Time courses of averaged photometric variables for BL (left column) and SSL (right column); a-b: illuminance on log scales (E_v); c-d: Colour Correlated Temperature (CCT); e-f: Colour Rendering Index (CRI); g-h: circadian weighted irradiance (Eec); MT (n=16): solid lines and ET (n=16): dashed lines (mean ± SEM); * = significant differences between MT and ET (p<0.05). Elapsed time on the x-axis was aligned relative to habitual wake time for both chronotypes.

In order to investigate the dynamics of light under different sky conditions, the photometric variables were analysed across 16 hours for all subjects (n=32). Significant interactions between the factors 'time' and 'sky conditions' were found under BL and SSL conditions for most photometric variables, except CCT and CRI under SSL conditions (Figure 5.8). Post-hoc analyses revealed significant differences between the three sky conditions, predominantly during the first 8 hours of the study, when daylight was available (Figure 5.8b-c, g-h; 2-way rANOVA; Duncan's multiple range test: $p<0.05$). Under SSL conditions, CCT and CRI were similar for the three sky types (Figure 5.8d-e).

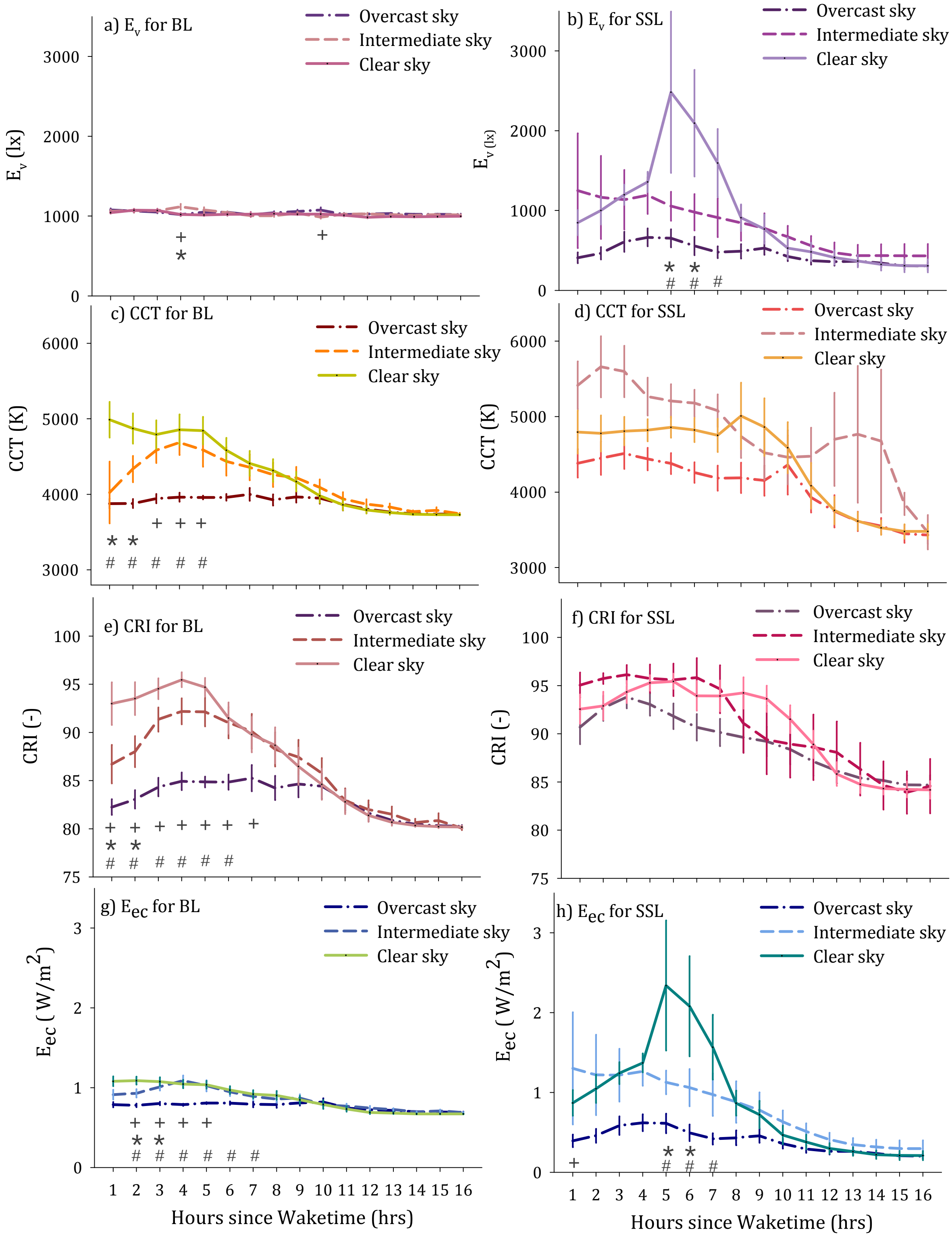

Figure 5.8: Time courses under BL and SSL conditions for physical light properties under different sky conditions for all study sessions (BL: n=32; SSL: n=32); a-b: illuminance (E_v); c-d: Colour Correlated Temperature (CCT); e-f: Colour Rendering Index (CRI); g-h: circadian weighted irradiance (E_{ec}); overcast sky = dashed-dotted lines, intermediate sky = dashed lines and clear sky = solid lines (mean ± SEM); + = significant differences between intermediate and overcast sky ($p<0.05$); # = significant differences between clear and overcast sky ($p<0.05$); * = significant differences between clear and intermediate sky ($p<0.05$).

Visual comfort variables

All visual comfort variables showed significant lower values for DIM conditions than for the other two lighting conditions (5-way rANOVA; main effect of 'condition'; Duncan's multiple range test; p< 0.05; Figure 5.9), except for two items: subjective glare ratings and "too much light to work" ratings. The BL conditions led to more glare sensations and "too much light for work" ratings compared to DIM and SSL conditions (p<0.05; Figure 5.9 b) and c). Moreover, subjects rated higher light preference and visual comfort under SSL than BL conditions (5-way rANOVA; 'time' x 'conditions' x 'chronotype' x 'gender' x 'order' interactions; Duncan's multiple range test; p<0.05; Figure 5.9 a).

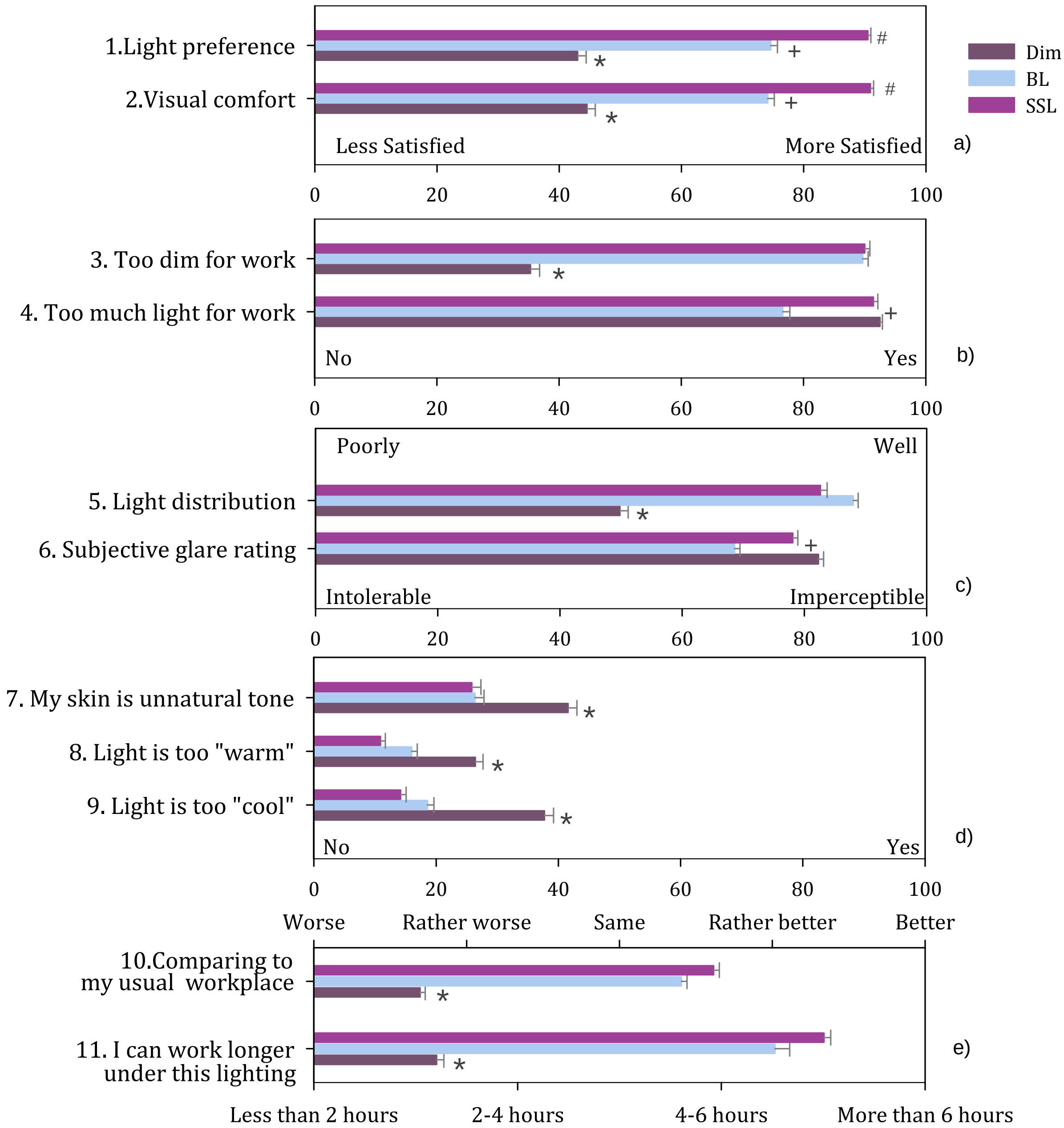

Figure 5.9: Averaged visual comfort variables for all lighting conditions (N=32). DIM = brown bars; BL = blue bars and SSL = pink bars (mean ± SEM); * = significant differences between DIM and the other two

conditions; += significant differences between BL and the other two conditions; #= significant differences between SSL and the other conditions (p<0.05).

Overall, there was a significant decrease of light preference and visual comfort towards the end of the study, regardless of the 'chronotype' as a variable (between 12-14 hours and 16 hours after habitual wake-time; main effect of 'time'; Duncan's multiple range test; p<0.05; not shown). Only for BL conditions there were significant differences between MT and ET (5-way rANOVA; 'chronotype' x 'time'; Duncan's multiple range test; p<0.05); ET showed higher light preference under BL conditions five hours after wake-time, when compared to MT (Figure 5.10a). They also expressed a better visual comfort (under BL), one and four hours after habitual wake-time (Figure 5.10c).

No significant difference with the factors ´time' or 'chronotype' was found for the SSL conditions (p>0.50; Figure 5.10 b and d). Overall, there were no significant differences regarding the factor 'gender' or 'order' for visual comfort variables for the three different lighting conditions (p>0.25).

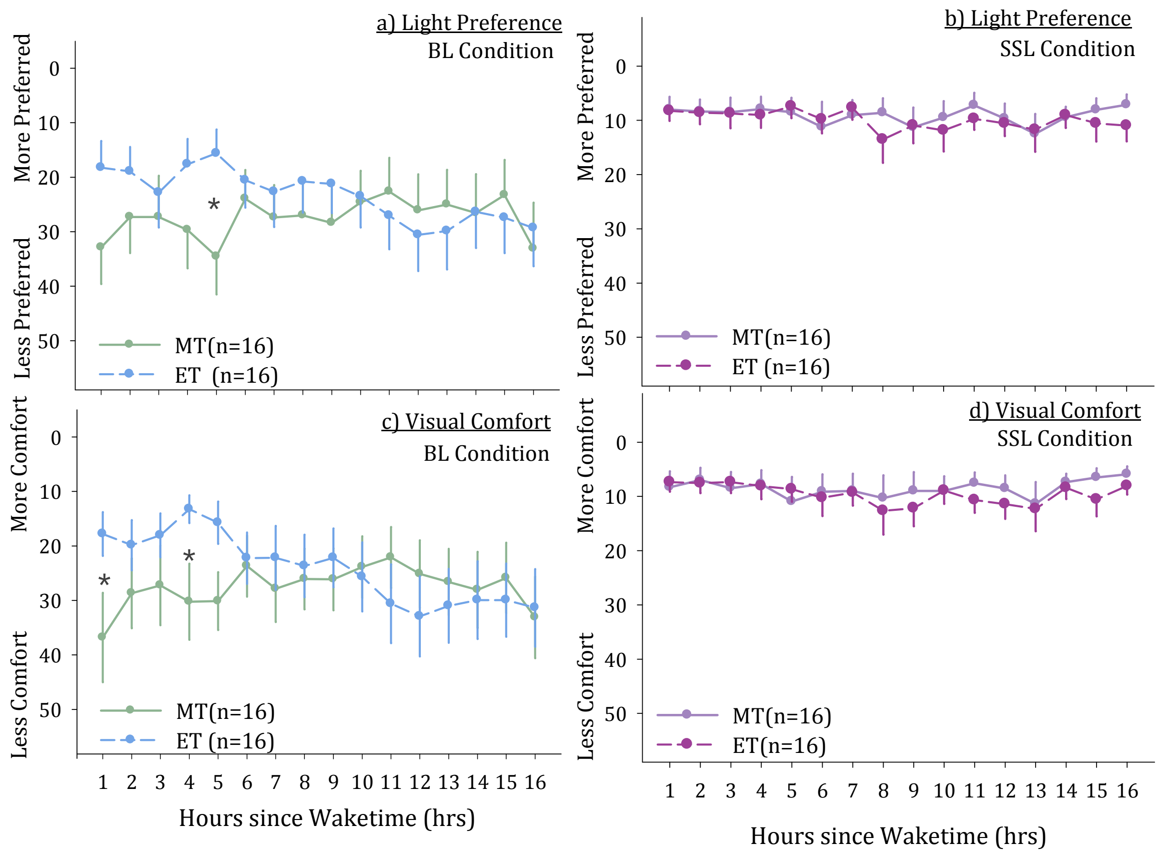

Figure 5.10: Averaged time courses of both chronotypes for: light preference (a-b); visual comfort (c-d) under BL (left column) and SSL conditions (right column). MT (N=16): solid lines and ET (N=16): dashed lines (mean ± SEM); * = significant differences between MT and ET (p<0.05).

The subjective glare ratings varied also over time (5-way rANOVA; main effects of 'time'; p<0.05); however they did not increase towards the end of the study as was the case for light preference and visual comfort. Compared to the first hour, lower glare sensations were expressed 8 and 10 hours after wake-time. Later on, no difference compared to the beginning of the study was found until the study end (5-way rANOVA; 'time' x 'condition' x 'chronotype' x 'gender' x 'order' interactions; Duncan's multiple range test; $p>0.05$).

In a next step, BL and SSL conditions were analysed separately for different sky conditions. In BL, subjects expressed lower ratings for discomfort glare under intermediate skies than under overcast skies (2-way rANOVA; main effect of 'sky conditions', $p<0.05$). Compared to overcast skies, subjects rated less discomfort glare under an intermediate sky 5, 8-9, 14 and 16 hours after their habitual wake-times; they also rated less discomfort under clear skies three hours after their wake-time (2-way rANOVA; 'time' and 'sky ' ; Duncan's multiple range test; $p<0.05$; Figure 5.11). There was no impact of sky conditions on subjective glare ratings under SSL conditions (2-way rANOVA; $p>0.50$), and no effect of sky conditions on the other visual comfort variables ($p>0.08$).

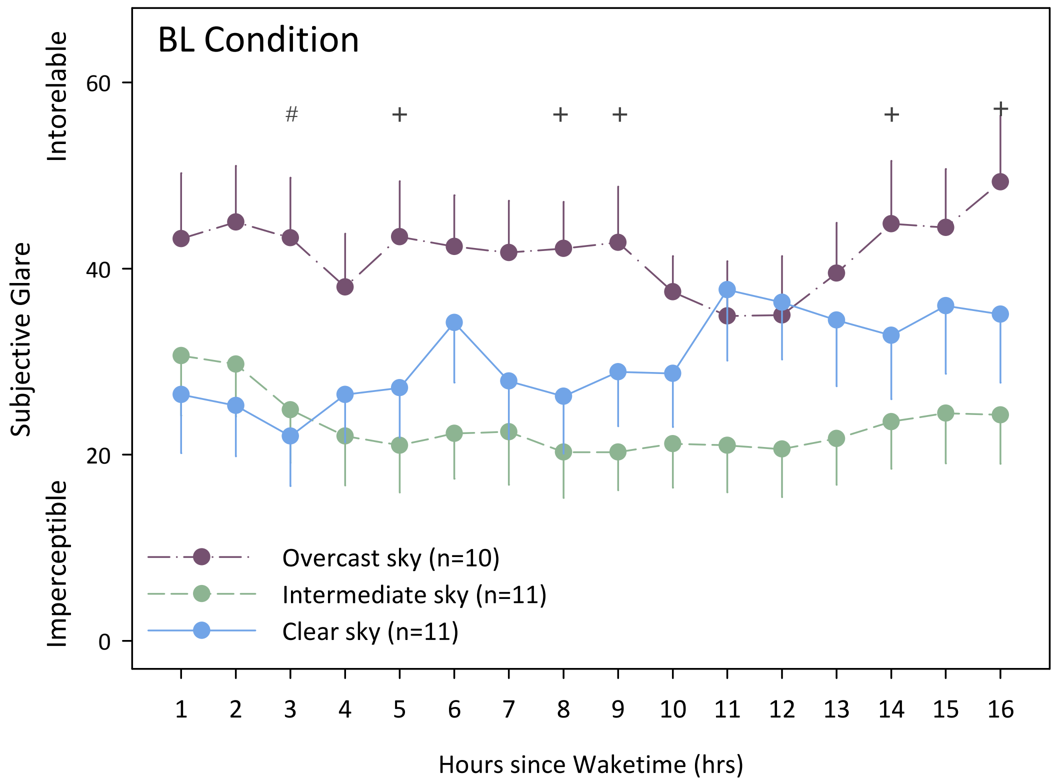

Figure 5.11: Effects of weather on subjective glare over time under BL conditions; overcast sky = brown circles; intermediate sky = green circles; clear sky = blue circles (mean ± SEM); + = significant differences between intermediate and overcast skies ($p<0.05$); # = significant difference between clear and overcast skies ($p<0.05$); n= numbers of subjects during the respective weather condition.

Non-visual functions

Subjective alertness, mood, physical well-being as well as relaxation varied over time during the study sessions (5-way rANOVA; main effect of 'time'; $p< 0.05$). The subjects reported lower alertness, a worse mood and worse physical well-being after nine hours since their wake-time, and they felt less relaxed after 12 hours (Duncan's multiple range test; $p<0.05$). They felt less alert, less physically well and less relaxed under DIM conditions, when compared to BL and SSL conditions (5-way rANOVA; main effect of 'condition'; Duncan's multiple range test; $p<0.05$).

There was, however, no significant 'condition' effect on mood ($p>0.78$). Overall, there were no significant differences between chronotypes on subjective assessments for BL and SSL conditions.

The time courses of those assessments were analysed separately for each lighting condition and the three different skies. Under SSL conditions, the subjects felt significantly sleepier (less alert) under an overcast sky compared to intermediate or clear skies (2-way rANOVA; main effect of 'sky condition', $p<0.05$). Compared to overcast skies, they rated to be significantly more alert under an intermediate sky 9 to 13 hours after their habitual wake-time, as well as 11 hours after their wake-time under clear sky conditions (2-way rANOVA; 'weather' and 'time' interactions; Duncan's multiple range test, $p<0.05$; Figure 5.12 a). A significant interaction was found for mood: the subjects were in a better mood under a clear sky during the last hours of the study, when compared to an intermediate sky (2-way rANOVA; 'weather' and 'time' interactions; Duncan's multiple range test, $p<0.05$), as shown in Figure 5.12 b). There was no impact of 'sky condition' on alertness and mood under BL conditions.

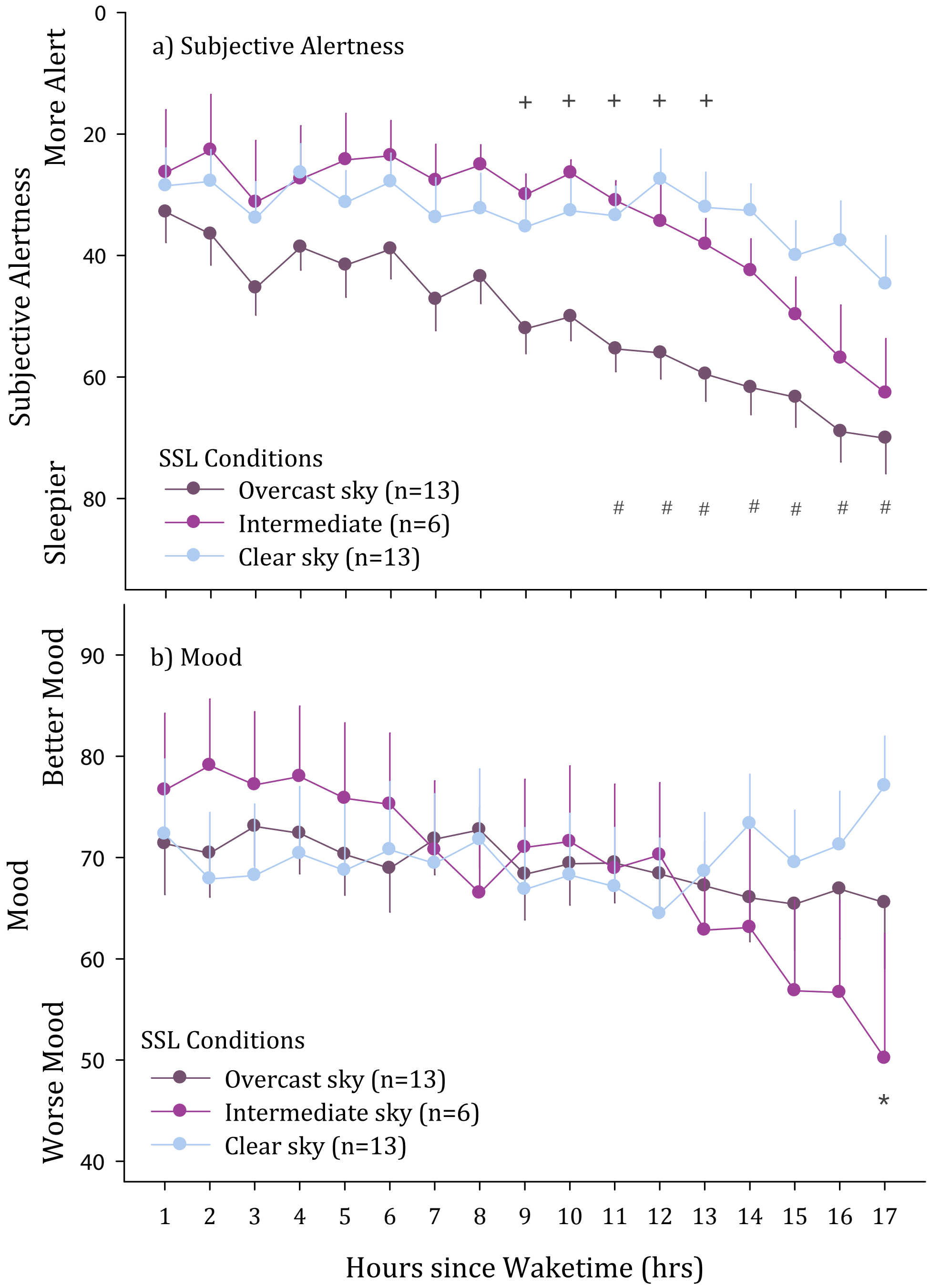

Figure 5.12: Time courses under SSL (N=32) conditions for: a) subjective alertness; b) mood; overcast sky = brown circles; intermediate sky = pink circles; clear sky = blue circles (mean ± SEM); + = significant differences between intermediate and overcast skies ($p<0.05$); # = significant difference between clear and overcast skies ($p<0.05$); * = significant difference between clear and intermediate sky ($p<0.05$); n= numbers of subjects during the respective sky condition.

Correlations analysis

The physical light properties under BL and SSL conditions were then correlated with subjective assessments, such as visual comfort variables and non-visual functions. Photometric variables showed small but significant correlations with both visual comfort variables and non-visual functions under all lighting conditions (Pearson's correlation; $p<0.05$). It must be outlined that vertical illuminance under BL conditions could not be used for the correlation analysis with the other variables, since it was maintained constant at 1000 lx.

Correlations between physical light properties and visual comfort variables

Table 5.9 a) shows the correlation coefficients (r) for visual comfort variables. Higher E_v, CCT, CRI and E_{ec} were positively correlated with greater light preference and visual comfort as well as longer working hours. Higher values of photometric variables were also associated with less feeling of "too cold" and "too warm" light hues. Lower CCT, CRI and E_{ec} values were associated with significantly larger glare sensations, more feeling of "too much light to work" and less natural skin tone.

For the lighting distribution, higher CRI and E_{ec} were associated with a poor light distribution under BL conditions. On the other hand, higher illuminance and E_{ec} were linked with a better light distribution under SSL conditions. Visual comfort variables were associated with the colour appearance of light under BL conditions, such that higher CCT, CRI and E_{ec} were correlated with better visual comfort and light preferences; under SSL conditions, neither CCT nor CRI were correlated with the latter. Better light preference and visual comfort were related in this case to larger E_v and E_{ec} values. Interestingly, only E_{ec} was positively correlated with visual comfort and light preference under both BL and SSL conditions.

Correlations between light properties and non-visual functions

The significant correlation coefficients (r) are shown in Table 5.9 b) (Pearson's correlation; $p<0.05$). Larger values of E_v, CCT, CRI and E_{ec} were positively correlated with more relaxation, better physical well-being and greater alertness under both conditions. Mood was influenced by the colour appearance of light, such that positive correlations of better mood with larger CCT, CRI and E_{ec} values were found, but no significant correlations of mood with E_v.

Correlation Coefficient	Higher Ev		Higher CCT		Higher CRI		Higher Eec	
	BL	SSL	BL	SSL	BL	SSL	BL	SSL
a) Visual comfort variables								
1. Greater light preference	x	0.12	0.23	-	0.20	-	0.20	0.11
2. Better visual comfort	x	0.11	0.26	-	0.25	-	0.24	0.11
3. Too dim light to work	x	-0.13	-	-	-	-	-	-0.12
4. Too much light for work	x	-	-0.32	-	-0.29	-0.10	-0.28	-
5. Better-distributed light	x	0.12	-	-	-0.15	-	-0.13	0.11
6. More subjective glare rating	x	0.09	-0.37	-0.11	-0.30	-0.10	-0.30	-
7. My skin is more natural tone	x	-	0.18	-	-	0.10	0.11	-
8. Light is too "warm"	x	-0.12	-0.15	-0.19	-	-0.16	-0.11	-0.13
9. Light is too "cool"	x	-0.13	-0.13	-	-0.11	-0.09	-0.09	-0.12
10. This lighting is worse than my usual workplace	x	-	0.12	-	0.16	-	0.12	-
11. I can work longer under this lighting	x	0.15	0.11	-	-	-	0.10	0.13
b) Non-visual functions								
1. More relaxed	x	-	0.16	0.17	0.10	0.25	0.18	0.10
2. Better physical well-being	x	0.10	0.24	0.25	0.24	0.33	0.26	0.15
3. More alert	x	0.19	0.20	0.20	0.22	0.27	0.24	0.22
4. Better mood	x	-	0.18	0.20	0.11	0.18	0.15	0.10

Table5.9: Correlation coefficients (r; Pearson's correlation) of photometric properties with visual comfort variables, and non-visual functions; only significant correlation coefficients are indicated ($p<0.05$) are shown (- = $p>0.05$);

Inter-correlations of visual comfort variables

In a next step, the intercorrelations with dependent visual comfort variables were investigated (Table 5.10a). As expected, visual comfort and light preference were highly correlated ($r>0.88$; $p<0.001$). Both variables showed high correlation coefficients with subjective glare ratings such that greater light preferences and visual comfort were associated with lower subjective glare ratings and longer working hours under these conditions ($r>0.41$; $p<0.001$). Lower visual comfort and lower light preferences were related to more feelings of "cold" and "warm" light, as well as a "too much light to work" ($r>0.58$; $p<0.001$).

Inter-correlations between visual comfort variables and non-visual functions

Furthermore, the visual comfort variables were correlated with non-visual functions, as shown in Table 5.10 c). Several positive correlations were found: more relaxation, better physical well-being, greater alertness and better mood were related to better visual comfort and greater light preferences under BL conditions; no significant correlations were found under SSL conditions. The aforehand mentioned non-visual functions were also negatively correlated with the feeling of too "cold" or too "warm" light. Better moods were associated with a better luminous distribution, more natural skin colour appearance and sufficient light to work under BL conditions (Table 5.10 b; r>0.34; p<0.001). Less relaxation and worse physical well-being showed small, but significant correlations with higher ratings of "too much light for work" and more subjective glare under both lighting conditions (Table 5.10b; r>0.09; p<0.05).

Inter-correlations of non-visual functions

The dependent non-visual functions were also inter-correlated, as shown in Table 5.10 d). High correlations were found between greater relaxation and better mood and better physical well-being (r>0.72; p<0.001). The latter showed also high correlations with greater alertness and better mood (r>0.48; p<0.001).

Positive Correlation Coefficient	Higher light preference		Better visual comfort		More relaxed		Better physical well-being		More alert		Better mood	
	BL	SSL	BL	SSL	BL	SSL	BL	SSL	BL	SSL	BL	SSL
a) With in visual comfort variables					b) Visual comfort variables and non-visual functions							
1.Higher light preference	x	x	0.92	0.88	-	0.17	-	0.09	-	0.17	-	0.17
2.Better visual comfort	0.92	0.88	x	x	-	0.17	-	0.09	-	0.13	0.11	0.18
3.Too dim light for work	-	-0.23	-	-0.25	-0.15	-	-0.17	-	-	-	-0.43	-0.17
4.Too much light for work	-0.58	-0.18	-0.66	-0.24	-0.12	-0.24	-0.15	-0.20	-	-0.09	-0.32	-0.17
5. Better-distributed light	0.13	0.29	0.10	0.29	-	0.17	0.11	0.26	-	-	0.36	0.28
6. More subjective glare	-0.58	-0.43	-0.63	-0.44	-0.09	-0.20	-0.13	-0.20	-	-	-	-0.09
7. Colour skin is more natural	-0.11	0.17	-	0.20	0.16	-	0.23	0.16	-	-	0.34	0.32
8. Light is too "warm"	-0.17	-0.21	-0.24	-0.23	-0.23	-0.20	-0.22	-0.23	-	-0.09	-0.32	-0.23
9. Light is too "cold"	-0.40	-0.43	-0.44	-0.45	-0.13	-0.19	-0.16	-0.15	-0.12	-0.09	-0.32	-0.19
10. This lighting is worse than my usual workplace	-0.23	-0.30	-0.21	-0.30	0.11	-0.14	0.09	-	0.17	-	-	0.10
11.I can work longer under this lighting	0.41	0.54	0.43	0.53	-	0.13	-	-	-	0.16	0.09	0.13
c) Non-visual functions and visual comfort variables					d) Within non-visual functions							
1. More relaxed	0.17	-	0.17	-	x	x	0.78	0.72	0.45	0.34	0.54	0.51
2. Better physical well-being	0.09	-	0.09	-	0.78	0.72	x	x	0.53	0.48	0.59	0.52
3. More alert	0.17	-	0.13	-	0.45	0.34	0.53	0.53	x	x	0.34	0.34
4. Better mood	0.17	-	0.18	0.11	0.54	0.51	0.59	0.59	0.34	0.34	x	x

Table 5.10: Correlation coefficients (Pearson's correlation; r) between and within visual comfort variables and non-visual functions; only significant correlation coefficient where p<0.05 are indicated. (- = p>0.05).

5.2.3 Discussion

This study showed (as expected from the literature) that all subjects experienced a better visual comfort and greater lighting preference under SSL than under BL conditions. Under BL conditions, most of the visual comfort variables significantly decreased at the end of the study. Significant differences between chronotypes were shown under BL conditions: MT chronotypes expressed lower visual comfort and lower light preference than ET chronotypes at the beginning of the study. Under BL conditions, subjective glare was rated as more intolerable under overcast sky than intermediate and clear skies at different times. The glare ratings varied over time but did not decrease towards the end of the study. For non-visual functions, subjective alertness, mood and well-being decreased over time. Most subjective assessments such as alertness, relaxation and physical well-being were rated significantly lower under DIM conditions when compared to BL and SSL conditions (except mood). Furthermore, under SSL conditions, the subjects expressed greater sleepiness under overcast skies than under intermediate or clear sky conditions. Mood was also differently assessed under those skies: mood was rated better under a clear sky than under an intermediate sky during the last hour of the study.

Assuming that the BL and SSL lighting conditions were realistic office lighting scenarios, the SSL conditions would correspond to office lighting with individual controlled systems, while the BL conditions mimicked realistic office lighting with centrally controlled systems. The automated control systems were targeting a 1000 lx threshold at subjects' eye; this lighting condition provides a saturating stimulation for the non-visual system according to the study of Cajochen et al. [193]. The effects of visual comfort between chronotypes were only observed under BL conditions: MT chronotypes rated lower visual comfort (one and four hours after their wake-time) and indicated less light preference (five hours after their wake-time) than ET. This cannot be explained by illuminance differences since illuminance was kept constant in BL conditions for both chronotypes. Lower CCT and CRI values for MT, under BL conditions, compared to ET might have contributed to lower visual comfort ratings for MT at the beginning of the study, but not after 4 hours, when physical light properties were the same for both chronotypes (Figure 5.7).

Interestingly, subjects expressed more glare sensations under overcast sky conditions than under the other sky types at different times; although daylight availability was higher for intermediate and clear skies compared to an overcast sky. It is very likely that some complementary electric lighting was added under overcast skies in order to reach the 1000 lx vertical illuminance target for BL conditions. In fact, there was some evidence from the study presented in Section 5.1 as well as from previous studies [23, 45, 49, 258] that the subjects usually rated higher glare sensations under electric lighting than under daylighting. This might explain the higher glare sensations expressed under overcast sky conditions. It is also possible that the different skies provided varying daylight fluxes into the room, which contributed to different luminous distributions; this point will be discussed further in the next chapter.

Under SSL conditions, which are considered as individually controlled lighting systems, the subjects chose vertical illuminance values mostly depending on daylight availability across daytime hours. This is in agreement with previous studies showing that under individually controlled systems, the artificial lighting is switched on only when the (indoor) daylight workplane illuminance is minimal [76, 269-271]. Photometric properties of light varied over time, and under SSL also according to the subjects' choices. They rated SSL conditions as extremely high regarding visual comfort and light preference; those assessments did not decrease over time. Previous studies by Moore et al. also reported the wide range of illuminance and high satisfaction ratings under individually controlled office lighting [76, 272]. Regarding the sky conditions, no influence of weather was found for visual comfort or light preference either under BL or under SSL conditions. This is not in agreement with a previous study by Laurentin et al. [248], showing that the subjects rated visual comfort as more pleasant under clear sky compared to overcast sky. It might be that in that study subjects were exposed to the view out of the windows, while in our study, no outside view was allowed. It is also possible that unpleasant lighting situations were prevented by the individual light conditions of the subjects.

Compared to DIM conditions (with almost no light), the two realistic office lighting scenarios BL and SSL indicated absolute effects of 'light' on the office workers. Light affected clearly the visual comfort variables as well as subjective alertness and well-being; however, no direct effect on mood was found. From the literature is known that besides psychiatric disorders [224], light can also directly impact on mood in healthy subjects [211, 215]. In a previous study, a better mood was found during sunny days comparing to cloudy days; this was true even for people working within buildings [210]. Similarly, better mood was observed under clear skies significantly longer than under intermediate skies at the end of the day [210].

For subjective alertness, although there was no significant effect between BL and SSL conditions, changes of subjective sleepiness under SSL than BL conditions (in comparison to the first hour) were previously reported [266]; this was explained by lower illuminance in the second half of the SSL sessions, when lower lighting conditions were chosen according to subjects' choice [266]. Subjects rated themselves to be less alert under SSL conditions for overcast skies than for the other two sky types. The greater daylight availability under intermediate and clear sky conditions accordingly prevented sleepiness from the middle until the end of the day. This is in agreement with many studies showing that exposure to bright daylight can reduce sleepiness [236] and that higher light intensity during daytime led to greater alertness during the day [190, 196]. Interestingly, when we examined the average illuminance and E_{ec} for these sky conditions, overall intermediate and clear sky provided larger E_{ec} values (not illuminance in the case of intermediate sky; Table 5.6) than overcast sky. This shows the impact of light on non-visual functions, which obviously respond better to circadian metrics (according to C-λ) than to photometric quantities (according to V-λ).

Overall, fewer correlations between photometric light properties and visual comfort variables were found under SSL than under BL conditions; this might be due to the variety of light flux under SSL than BL conditions, as well as due to subjects expressing very high visual comfort ratings under SSL. Those high assessments did not change over time unlike under BL conditions. It appears that the perception of visual comfort varied throughout their preferred lighting conditions, not the physical properties of light, *per se*. However, when considering non-visual functions, most of the variables were positively correlated with photometric variables under both conditions. Interestingly, this might imply that the subjects' non-visual functions were not influenced by their light preference; subjective alertness, well-being and mood were however directly influenced by the physical properties of light. As mentioned above, visual discomfort might be prevented by individual lighting preference; however, subjective alertness, well-being and mood might not be improved by lighting preference.

Lastly, visual comfort and light preference showed significant correlations with both illuminance and colour appearance, such as CCT and CRI. Under BL lighting conditions, where the vertical illuminance was maintained constant around 1000 lx, better visual comfort and light preference correlated with higher CCT, CRI and E_{ec}. Conversely, under SSL conditions, the same variables were correlated positively with higher illuminance and $E_{ec;}$ no correlations with CCT or CRI were found however. It is interesting to further investigate whether E_{ec} can be an accurate predictor of subjective visual comfort in further studies. Moreover, a better lighting distribution correlated with a higher E_{ec} under SSL conditions. The effects under BL conditions were the opposite: lower illuminance and lower E_{ec} were associated with a more optimal luminous distribution. The opposite correlations under SSL and BL conditions may also be explained by the luminous distribution; this is the objective of study of Chapter 6.

5.3 Conclusion

The first experiment confirmed the impact of light on visual comfort, subjective alertness, mood and well-being. The subjects became sleepier and expressed a lower physical well-being earlier under pure electrical light when comparing to daylighting conditions. These results showed that photometric light properties *per se*, can enhance our visual comfort since correlations showed an improvement of visual comfort and well-being with a larger daylight availability. Higher illuminance, CCT, CRI, E_{ec} and longer sunshine duration were also correlated with greater light preference, a better visual comfort and physical well-being, as well as more relaxation.

For the second experiment, under bright light conditions where the vertical illuminance at eye level was maintained constant at 1000 lx, visual comfort decreased in the course of the study, as well as light preference. Different sky conditions influenced also the subjective assessments, such as glare ratings: the latter were often observed under overcast sky conditions due to the complementary aspect of electric lighting.

When subjects were allowed to select their own lighting systems, they chose the one which involved daylighting all day. Visual comfort and light preference were rated very high; the corresponding assessments did not change over time. Different sky conditions had significant impacts on subjective alertness and mood. Under overcast sky conditions the subjects felt sleepier than under intermediate and clear sky conditions. Under clear sky, they expressed also better mood at the end of the study compared to intermediate sky conditions. Subjective alertness, well-being and mood had significant and positive correlations with illuminance and colour appearance, such as CCT and CRI, as well as circadian weighted illuminance E_{ec}.

Besides the photometric light properties, such as intensity and colour appearance, luminous distribution played also an important role regarding visual comfort. Assessments of overall luminance distribution, as well as objective glare sensations over time will provide a better comprehension of the light impact on visual comfort: this will be discussed in the next chapter.

Chapter 6 Discomfort glare and subjective assessments

Several glare indices have been developed to assess visual comfort [45, 51, 148, 273, 274] (see also Section 3.2). The avoidance of discomfort glare is however only one aspect to achieve high visual comfort. According to previous studies by Hopkinson [144], Chauvel [45], and Boyce and Beckstead [275], Velds [39] suggested that there might be several other factors involved in discomfort glare, such as photometric variables, weather conditions, time of day, outside view, prior experiences of subjects, and the subjects' state of mind. For this thesis, some of the above mentioned variables which are involved in discomfort glare were examined together with glare indices. The aim was to enlarge our current understanding of visual comfort mechanisms. It was further tested whether some non-visual functions were influenced by discomfort glare.

The data was obtained from two experimental studies with human subjects (see Chapter 5). Photometric features, such as vertical illuminance at the eye level, colour temperature (CCT), colour rendering index (CRI) and circadian weighted irradiance (E_{ec}), were correlated with subjective visual comfort assessments. Besides the light intensity and spectral composition, this chapter presents the discomfort glare ratings achieved during the two experimental studies (see Chapter 5). The high dynamic range imaging (HDR) technique, described in Chapter 3, was applied to capture a lit scene and to assess its luminance distribution. An ordinary CCD camera was used for that purpose in the first experiment (Section 6.1); a Camera-Like Light Sensor (CLLS; see Section 3.4) was used in the second experiment (section 6.2). The overall objective was to monitor the luminous distribution in an indoor environment over time, by using different glare indices, as well as background luminance determined by HDR images. Finally, the glare indices were associated with visual comfort variables and non-visual functions at different times of day.

6.1 Impact of discomfort glare on visual comfort, alertness and mood in realistic office day- and electric lighting conditions (Experiment I)

Discomfort glare was assessed in an indoor environment during the Experiment I, as described in Chapter 5 (Section 5.1): the corresponding results are presented in this Chapter. The glare indices determined during the afternoon as well as their associations with visual comfort parameters were investigated. Preliminary results were presented at a scientific meeting and published as conference proceedings [143].

6.1.1 Experimental methods

Study design

The study participants, the room setup and the study design are described in Section 5.1. In this study, HDR images from the indoor scenes under (mainly) daylighting conditions (DL) involved 22 subjects (for technical reasons, data from three subjects out of 25 could not be analysed). Subjects were exposed to daylight with a vertical target illuminance at the eye in the range of 1000 and 2000 lx (mean: 966 lx; SEM±94.8 lx). The lower window part of the test room was covered with textile blinds in order to prevent any outside view for the subjects. The upper part of the windows was equipped with Anidolic Daylighting Systems (ADS) which re-direct the daylight flux to the ceiling and to the rear of the room [252]; the sky vault was partly visible for the subjects through the corresponding upper window. Electric lighting (from six ceiling mounted luminaires: 58W, 3000K) completed the office room lighting, when vertical illuminance dropped below 1000 lx. Subjects came 4-5 hours after their habitual wake time to the laboratory and spent the afternoon (from noon to 6PM) in the test room in a steady sitting position. They were allowed to read, work or listen to music; but they were not allowed to perform computer work. Figure 5.1 a) in Section 5.2 shows the view of the test room with the windows.

HDR imaging

A sequence of 14 pictures was taken three times during each study afternoon (at 12PM, 3PM and 5:30PM), by using a calibrated camera with a fisheye lens (Nikon Coolpix 5400; FCE-9 lens). The camera was mounted on a tripod and placed next to the subjects. The camera sensor was oriented in the gazing direction of the subjects. Exposure times were set in the range of 2s to 1/4000th of a second with 4.0 F-stops for a bunch of snapshots, according to the HDR imaging technique (see Section 5.1). The 'white balance' was set to the 'daylight' position. Vertical illuminance was continuously recorded in 5 min intervals throughout the study by means of a spectroradiometer (Specbos 1201, JETI, Germany). HDR images were created as described in Section 3.3, by using the software 'Photosphere' (v1.8.7U, available on www.anyhere.com [160]).

Glare risks assessments

After generating a single HDR image, glare indices were determined by using the software 'Evalglare' (v0.9, Fraunhofer Institute, Germany) [148, 162]. Figure 6.1 shows a final image (obtained from the HDR imaging technique), with potential glaring sources (coloured areas) detected by 'Evalglare'. Three different glare indices were used as objective glare assessments: the Daylight Glare Probability (DGP) [148], the Daylight Glare Index (DGI) [45] and the Unified Glare Index (UGR) [276]. The vertical illuminance of each scene was also calculated by the software 'Evalglare'.

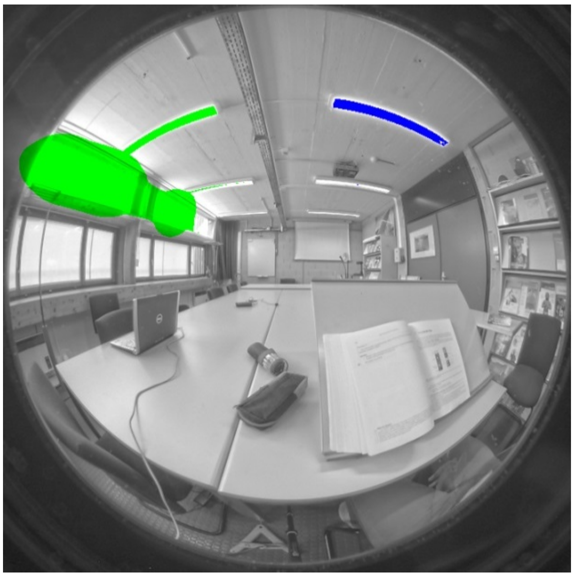

Figure 6.1: Sample HDR image corresponding to subject 'Liper29' at 12PM with potential glaring sources identified by the software 'Evalglare' [162].

Statistical analysis

The software Statistica v6.12 (StatSoft, USA) was used for statistical analyses. Firstly, Pearson's correlations were used to relate the vertical illuminance measured by the spectroradiometer and the calculated vertical illuminance. In the next step, glare indices were subjected to repeated analyses of variance (rANOVA; one-way repeated analysis of variance); post-hoc tests (Student t-tests) were applied to analyse potential variations over time. In the final step, the subjective non-visual function ratings, described in Section 5.1, were associated with those glare indices by using Pearson's correlations.

6.1.2 Results

Objective glare assessments

Vertical illuminance (as measured with a spectroradiometer), as well as the corresponding illuminance computed by Evalglare showed a significant correlation ($r = 0.84$; $p<0.001$). Both variables as well as the glare indices (DGP, DGI and UGR), determined by post-processing of the

HDR images, varied in the course of the afternoon (one-way rANOVA; $p<0.001$; Figure 6.2). The variation of discomfort glare was such that all glare indices (DGI, UGR, DGP) were significantly lower at 5:30PM, when compared to those earlier in the afternoon (t-tests; $p<0.05$).

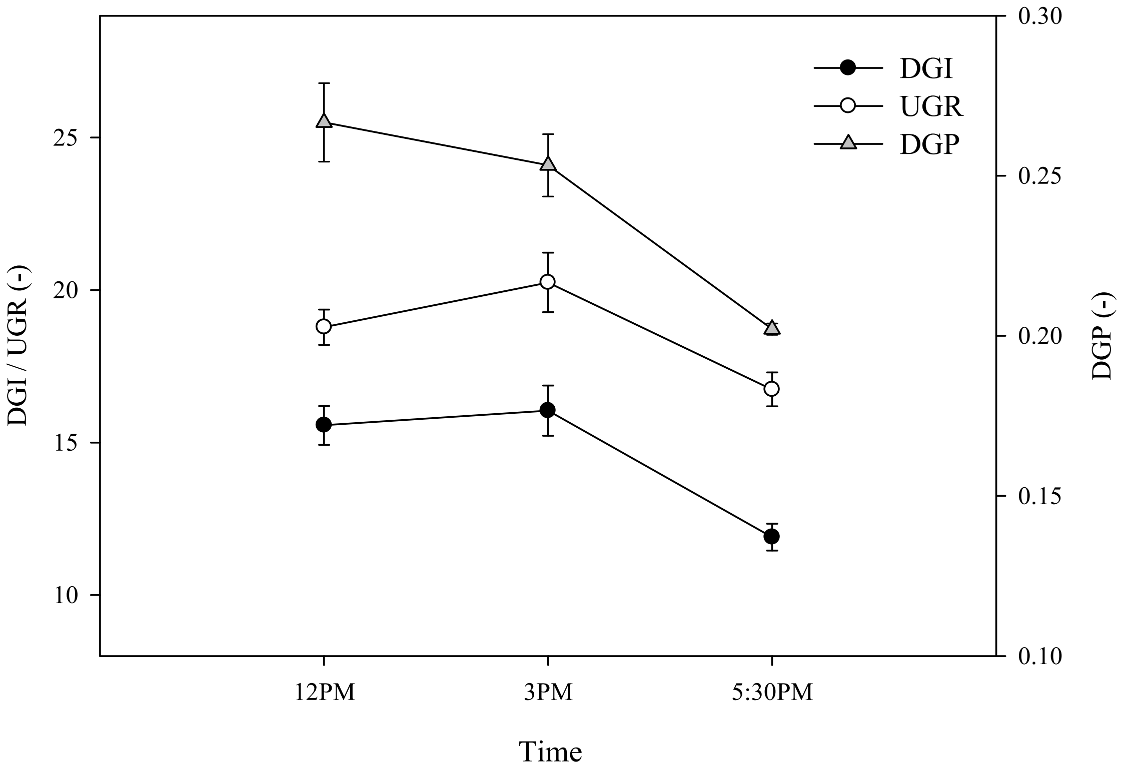

Figure 6.2: Dynamics of averaged glare indices (mean ± SEM) in the course of the afternoon; DGP = Daylight Glare Probability, DGI = Daylight Glare Index, UGR = Unified Glare Index; N=22.

Associations of objective glare with subjective assessments

A lower subjective visual comfort was significantly correlated with the DGI in the middle of the afternoon, and showed a tendency with the UGR (3PM; $r = -0.44$ for DGI, $p<0.05$; for UGR: $r = -0.40$, $p< 0.1$; Table 6.1). Subjective light preference did not significantly correlate with the three glare indices (DGP, DGI and UGR), but showed tendencies at the beginning of the study ($r>0.37$; $p<0.1$; Table 1). There was no correlation between objective and subjective glare assessments ($p>0.1$; not shown).

Higher objective glare ratings (DGP, DGI and UGR) were significantly associated with lower subjective relaxation at 3PM ($r<-0.46$; $p<0.05$), and showed a tendency at 5:30PM ($r <-0.36$; $p< 0.1$). There were slight positive correlations at the beginning of the afternoon, such that higher DGP and UGR tended to relate to better physical well-being ($r>0.38$; $p< 0.1$); however, significant associations between the three higher glare indices and lower physical well-being were found at 5:30PM ($r<-0.48$; $p< 0.05$). Subjective alertness was negatively correlated with the DGP in the middle of the afternoon (3PM), such that larger glare indices were associated with lower subjective alertness ($r<-0.36$; $p<0.1$). Finally, we did not find significant correlations between the three glare indices and subjective mood assessments ($p>0.1$).

Subjective Assessments	Glare indices 12PM			Glare indices 3PM			Glare indices 5:30 PM		
	DGP	DGI	UGR	DGP	DGI	UGR	DGP	DGI	UGR
Visual comfort	-	-	-	-	−0.44*	−0.40#	-	-	-
				↑ glare	↓ comfort				
Light preference	0.37#	0.40#	0.38#	-	-	-	-	-	-
	↑ glare	↑ preferred							
Relaxation	-	-	-	−0.60*	−0.46*	−0.47*	−0.41#	−0.36#	−0.48*
				↑ glare	↓ relaxed		↑ glare	↓ relaxed	
Physical well-being	0.38#	-	0.40#	-	-	-	−0.50*	−0.48*	−0.59*
	↑ glare	↑ comfort					↑ glare	↓ comfort	
Alertness	-	-	-	−0.42*	−0.36#	−0.37#	-	-	-
				↑ glare	↓ alert				

Table 6.1: Correlation coefficients (r) between glare indices and subjective assessments (visual comfort, light preference, subjective well-being and alertness) at different times during the afternoon; * = $p< 0.05$, # = $p< 0.1$ (tendency), and – = $p>0.1$ (not significant). For significant values or tendencies, the directions of the correlation coefficients are indicated with arrows.

6.1.3 Discussion

Significant associations between less subjective visual comfort, less relaxation and lower alertness with higher glare indices were only found at 3PM. For physical well-being and relaxation there was a negative correlation also at 5:30PM. Since glare indices did not significantly vary between noon and 3:00PM (see Figure 6.2), it was rather the change of subjective assessments, not the change of indoor luminous distribution or the presence of glaring sources, which caused the opposite direction of the correlations between noon and 3:00PM. This may indicate that in the course of the afternoon subjects became more perceptive to the incidence of light distribution. The negative correlation at 5:30PM can also be explained by a change in illuminance due to the fading of daylight. The variations of subjective comfort in the course of a day were also described in Section 5.1 and are in agreement with previous results from Boyce et al. [17].

We could not find significant correlations between subjective glare ratings and glare indices, as reported by Wienold, even though similar glare assessments were used [249]. One explanation might be that the subjects could avoid discomfort glare caused by direct sunlight during the entire study: textile blinds were lowered to prevent any outside view, but also to avoid sunrays entering the test room. Secondly, the studies were undertaken in a room which was equipped with Anidolic Daylighting Systems [277, 278]. These systems provide a more even luminous distribution on the work plane and deeper in the room which reduces any glare risks associated to excessive luminance contrasts [151]. This is in agreement with the statement by Velds, indicating that glare indices were developed to assess discomfort glare. They are not appropriate for any windows or daylighting systems due to the different luminous distribution [39]; most of the glare indices were developed for electric lighting systems and point light sources. Finally, the sample size of the study might be too small. Further investigations regarding the effects of indoor luminous distribution on subjective assessments are needed to extend the study to larger populations and longer time episodes.

6.2 Impact of discomfort glare on visual comfort, subjective, alertness mood and well-being for various lighting conditions in extreme chronotypes (Experiment II)

6.2.1 Subjects and methods

Study design

The inclusion of extreme morning types (MT) and extreme evening types (ET) was described earlier in this thesis (see Chapter 5). Demographic details, the room setup and study design were described in details in Section 5.2.1. This section presents subjective assessments and indoor luminous distributions of 32 subjects (16 MT and 16 ET).

The study was conducted in a test room located in the LESO Solar Energy Experimental Building equipped with Anidolic Daylighting Systems; the lighting conditions were similar to those described in Section 5.2. Only bright light conditions (BL) and self-selected conditions (SSL) were used for objective glare assessment, since dim light conditions (DIM) were not considered as realistic office lighting conditions. Under BL conditions, the vertical illuminance was targeted at ~1000 lx throughout the entire session. Under SSL conditions, the subjects were asked to choose their lighting preferences each hour. Their choices comprised daylighting and/or electric lighting, as shown in Figure 5.5 and described in Table 5.6 (see Chapter 5).

Images of the scenes mimicking the subjects' view were recorded hourly during the 16 hours of the study under BL and SSL conditions using the Camera-Like Light Sensor (CLLS) described in Chapter 3. The image sequences of one subject could unfortunately not be recorded during the BL session, due to a technical problem (BL: n=31; SSL: n=32). For all study sessions, vertical illuminance at the eye level (E_v), correlated colour temperature (CCT), colour rendering index (CRI) and circadian weighted irradiance (E_{ec}) were continuously recorded in 5 min intervals throughout the study, using a spectroradiometer (Specbos 1201, JETI, Jena, Germany).

Visual comfort variables were assessed hourly, while subjective alertness, mood and physical wellbeing were examined every 30 minutes (see Section 5.2.1).

CLLS imaging

A digital image was captured and a video movie was recorded hourly, always after the subjective visual comfort assessments, using the software "DeviseIcyLightGUI" (which is an executable JAVA Graphical User's Interface for "IcyCAM") developed by CSEM. A total of 16 sequences of hourly images for each subject was analysed to assess the luminance distribution in the test room. In a next step, the software "ImageCAM", developed by LESO-PB/EPFL was used to produce an HDR image from each digital picture taken by the calibrated CLLS (see Section 3.2).

Glare ratings

Glare indices were calculated using Evalglare (Evalglare v1.11, Fraunhofer Institute, Germany) [148, 162], as described in Section 6.1. Background luminance as well as three different glare indices were used as glare risk assessments: Daylight Glare Probability (DGP) [148], Daylight Glare Index (DGI) [45] and Unified Glare Index (UGR) [276]. Figure 6.3 shows three images captured during a study session at different times of the day. Potential glare sources as identified by the software Evalglare are shown with coloured areas.

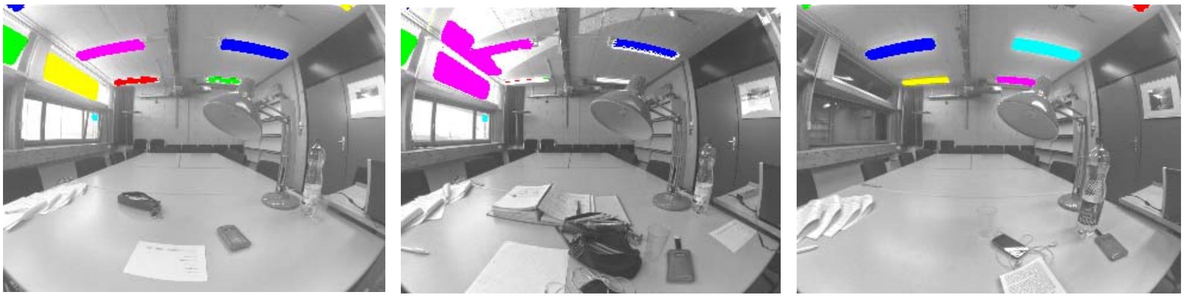

Figure 6.3: HDR images of subject 'Chroli 22', taken with the CLLS in the morning (left picture), in the afternoon (middle) and in the evening (right). The coloured areas indicate potential glare sources.

Statistics

The statistical analyses were carried out using the software Statistica 6.12 (StatSoft, USA). The analysis from subjective assessments of non-visual functions was described in Section 5.2. Data from objective glare assessments were analysed by first performing repeated analyses of variance (rANOVA) with two factors (2-way rANOVA): 'time' (16 time points) and 'condition' (BL and SSL). In a next step, subjective assessments were analysed separately for each lighting condition to investigate the effects of different sky types (overcast, intermediate and clear sky) at different times (2-way rANOVA; 'weather' x 'time'). Duncan's multiple range tests were applied for post-hoc analysis. Lastly, correlation analysis was performed using Pearson's correlations for normally distributed values.

6.2.2 Results

Objective glare assessments over time

Figure 6.4 illustrates the calculated glare indices (DGP, DGI and UGR), as well as the background luminance over time for both conditions (BL and SSL) across all subjects. Generally, glare indices were rather low (low glare); they were mostly below the borderline between comfort and discomfort (grey dashed line in Figure 6.4). All glare indices (DGP, DGI, UGR) as well as background luminance varied over time (2-way; ANOVA; main effect of 'time'; p< 0.001), except E_v for BL conditions. All glare indices and background luminances were significantly different between BL and SSL conditions, and several statistical interactions were found (2-way; ANOVA; main effect of 'condition'; p< 0.001; Figure 6.4). The DGP, DGI and background luminance were lower under SSL than BL at the beginning of the study (during the first hour). During the entire second half of the study, all glare indices (DGP, DGI and UGR) and background luminance were significantly lower under SSL, compared to BL conditions (2-way; ANOVA; p< 0.001; Figure 6.4). It is noted that time is relative to the habitual wake times of both subject groups (MT and ET) on Figure 5.4.

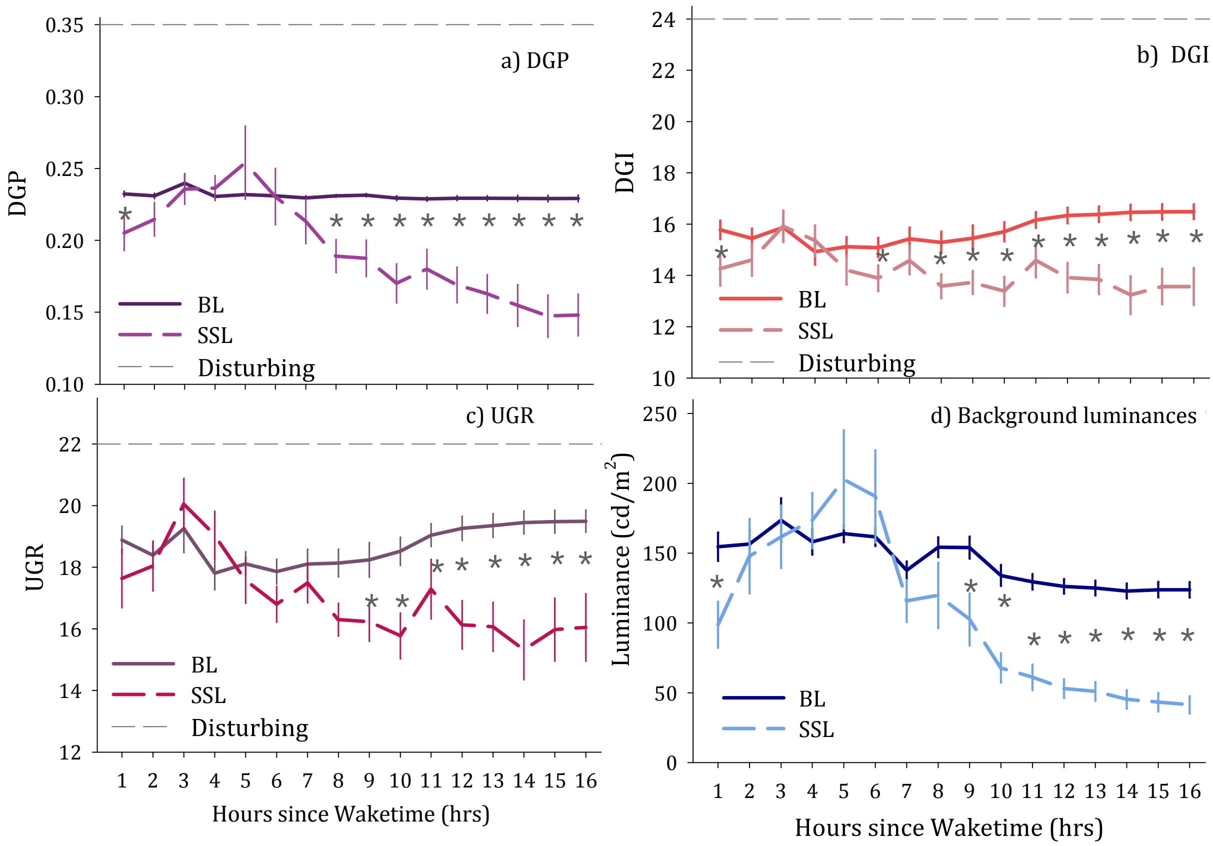

Figure 6.4: Averaged glare indices indicated relative to elapsed time since habitual wake time (mean±SEM) for DGP (a); DGI (b) UGR (c) and background luminance (d); BL conditions = solid line; SSL conditions = dashed line; *= p<0.05; dashed grey line=exceeding "disturbing" glare sensations. DGP = Daylight Glare Probability; DGI=Daylight Glare Index; UGR = Unified Glare Index (UGR)

For further analysis of the lighting environment, different weather conditions were characterized by determining three sky types (clear, intermediate and overcast), according to the Swiss Norm 150 911 [267], as described in Section 5.2.2.

The averaged DGP, DGI, UGR and background luminance for different skies are presented in Table 6.2 for BL and SSL conditions. Overall, glare indices were not significantly different between the three different weather conditions in BL. Only for SSL, background luminance differed between weather conditions; it was larger for clear skies and lower for overcast skies (Table 6.2 shows the corresponding averaged values; 2-way; ANOVA; main effect of 'weather'; p<0.05). An interaction between the factors 'time' and 'weather' was found, such that from five to six hours after habitual wake time, the DGP in SSL conditions was significantly lower for overcast than for clear skies (Figure 6.5a). Background luminance was significantly higher with clear than with overcast skies (and partly intermediate skies), up to the first six hours after habitual wake time during the SSL sessions (Figure 6.5 b). The DGI was significantly lower with intermediate than with clear skies after nine hours in BL conditions (Figure 6.5 c; 2-way rANOVA; $p< 0.05$).

Lighting conditions	Sky conditions	N	DGP (-) (mean ± SD)	DGI (-) (mean ± SD)	UGR (-) (mean ± SD)	Background luminance (cd/m^2) (mean ± SD)
BL	Overcast	10	0.232 ± 0.00	16.19 ± 1.27	19.09 ± 1.46	144 ± 24
	Intermediate	10	0.228 ± 0.02	15.18 ± 2.75	18.05 ± 3.31	133 ± 57
	Clear	11	0.232 ± 0.02	15.93 ±2.27	18.97 ± 2.64	152 ± 51
SSL	Overcast	13	0.181 ± 0.06	13.94 ± 3.46	16.73 ± 5.20	$64 \pm 51^{+\#}$
	Intermediate	6	0.206 ± 0.06	13.99 ± 2.56	17.17 ±3.30	$124 \pm 120^{+}$
	Clear	13	0.201 ± 0.11	14.40 ± 3.77	17.16 ± 4.83	$136 \pm 151^{\#}$

Table 6.2: Averaged glare indices and background luminance (mean ± SD) for different lighting conditions (BL and SSL) and different sky types; DGP=Daylight Glare Probability; DGI=Daylight Glare Index; UGR= Unified Glare Index (UGR); + = significant difference between intermediate and overcast sky ($p<0.05$); # = significant difference between clear and overcast sky ($p<0.05$);

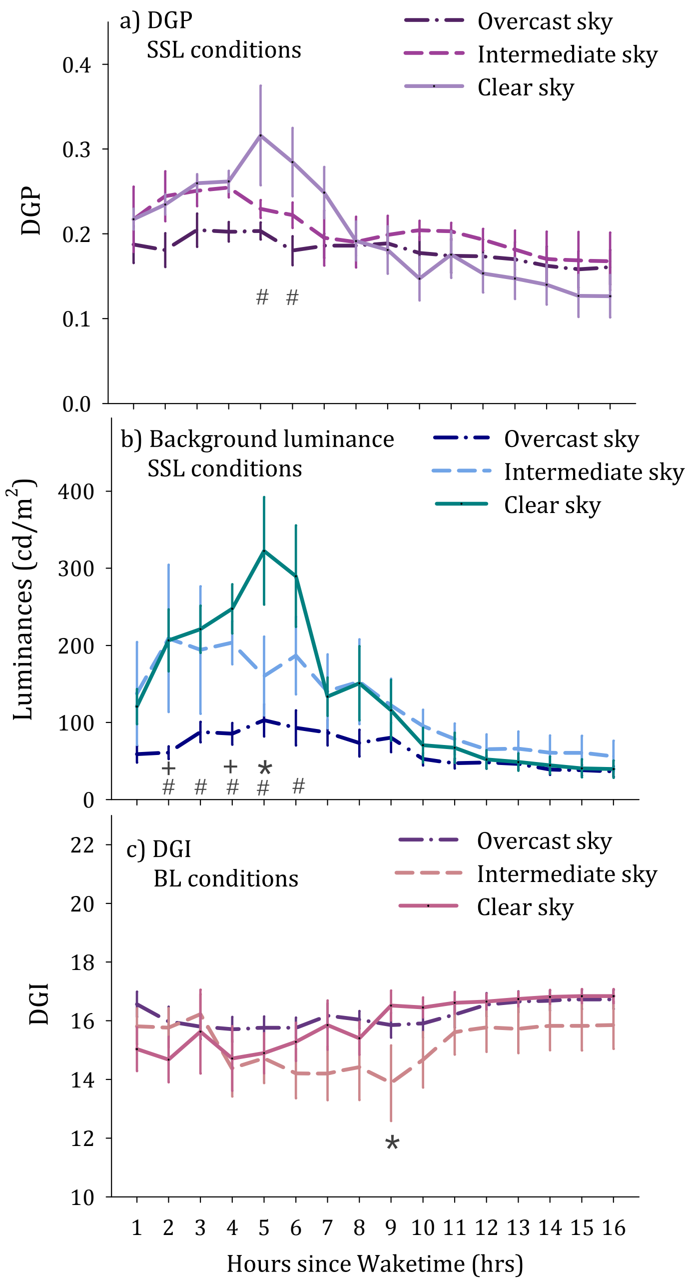

Figure 6.5: Time courses under BL and SSL conditions of average a) DGP; b) background luminances under SSL conditions; c) DGI under BL conditions; overcast sky = dashed and dotted lines, intermediate sky = dashed lines and clear sky = solid lines (mean ± SEM); + = significant differences between intermediate and overcast sky ($p<0.05$); # = significant difference between clear and overcast sky ($p<0.05$); * = significant difference between clear and intermediate sky ($p<0.05$; N=32).

Associations between visual comfort and non-visual functions

Glare indices and background luminances were correlated with subjective assessments, such as visual comfort variables and non-visual functions. Table 6.3 shows the corresponding significant correlation coefficients (r). Under BL conditions, higher glare indices (DGP, DGI and UGR) were correlated with lower lighting preference and poor visual comfort ($r<-0.13$; $p<0.05$). Larger glare indices were also associated with greater subjective glare and more feelings of “too much light to work” ($r<-0.13$; $p<0.05$). DGP, DGI and UGR were not correlated with subjective luminous distribution in the room, except for higher background luminance. Interestingly, under SSL conditions, the correlations went in the opposite way, when compared to those under BL conditions. Larger glare indices were correlated with higher lighting preferences, better visual comfort, 'sufficient light to work' and a more even luminous distribution (r>0.12; p<0.05). Only higher DGI correlated with more subjective glare (r>0.09; p<0.05). Background luminance did not correlate at all with any of the subjective visual comfort or glare assessments under SSL condition.

Significant correlations between glare indices and non-visual functions were found mostly under BL conditions. Higher objective glare indices were correlated with less relaxation, worse physical well-being, lower alertness and worse mood (Table 6.3). The DGI and UGR showed no significant correlations with non-visual functions (p>0.05). For SSL conditions, a higher DGP was related to greater alertness.

Lighting conditions	Subjective variables	Higher DGP	Higher DGI	Higher UGR	Higher Background luminance
BL	Lower light preference	0.13	0.25	0.24	-
	Lower visual comfort	0.14	0.27	0.27	-
	More sufficient to work	-	-	-	-
	Too much light to work	0.19	0.38	0.37	-
	Worse luminous distribution	-	-	-	0.13
	More subjective glare	0.23	0.41	0.39	-
	Less relaxed	-	0.17	0.18	0.15
	Worse physical well-being	-	0.21	0.21	-
	Lower alertness	-	0.22	0.23	-
	Worse mood	0.10	0.19	0.21	0.16
SSL	Higher light preference	0.13	0.12	0.13	-
	Higher visual comfort	0.12	0.12	0.12	-
	More sufficient to work	0.17	0.21	0.22	-
	Too much light to work	-	-	-	-
	Better luminous distribution	0.09	0.11	0.11	-
	More subjective glare	-	0.09	-	-
	More relaxation	-	-	-	-
	Better physical well-being	-	-	-	-
	Greater alertness	0.14	-	-	-
	Better mood	-	-	-	-

Table 6.3: Correlation coefficients between glare indices (DGP, DGI, UGR) and visual comfort variables and non-visual functions (alertness, relaxation, physical wellbeing and mood); p<0.05, - = p>0.05 (N=31).

6.2.3 Discussion

The results show that glare indices did not exceed the 'disturbing' level of the glare index scales; they were, however, different under BL and SSL conditions. Under SSL conditions, a decrease of all glare indices and background luminance was observed from the beginning towards the end of the study. Slight effects of weather conditions were found for DGP, DGI and background luminances at different times of the day. The different lighting conditions (BL and SSL) showed opposite directions in their correlations between glare indices with subjective assessments. Larger glare indices were associated with poorer visual comfort, less alertness, worse well-being and mood under BL conditions. On the other hand, under SSL conditions, larger glare indices were associated with better visual comfort and greater alertness.

In the second study, several correlations between glare indices and subjective glare ratings were observed even though the first study did not show any correlations between these variables. It was assumed earlier that glare indices reflect less glare sensations in the presence of daylighting systems (such as Anidolic Dayligting Systems and/or textile blinds). This assumption can be debated since the second study was conducted in the same room with the same daylighting systems. The most likely reason for the somehow inconsistent findings might be the study duration, which lasted for 16 hours. This was more than double as long as the study duration in the first experiment and showed the dynamics of daylight in the course of an entire working day. During this time, subjective assessments also varied. Related to the latter might be that the study was performed with extreme chronotypes. Consequently the inter-individual range of assessments was larger and the study was designed to scrutinise some of those differences. Whether their internal different circadian phase might also have contributed to the observed associations with visual comfort and non-visual functions will be further analysed.

A new and interesting finding of the study was that opposite correlations were found between BL and SSL conditions for visual comfort and subjective glare ratings. Individually controlled lighting reflected subjectively preferred lighting conditions and might prevent any negative glare sensations, regardless of access to an outside view. A second reason might be that SSL conditions enabled a situation where subjects could actively adjust the lighting to be comfortable.

It is important to note that the glare indices were developed for different lighting situations: the UGR was recommended in particular for artificial lighting [51, 273]. During BL conditions, the DGP did not vary over time; it is possible that DGP is not so strongly influenced by the variation of luminance [148]. Another reason might be that the vertical illuminance was kept approximately at 1000 lx throughout the study. The other parameters of DGP were not ample enough to alter the latter in this study.

During BL conditions, electric light was added over time, particularly at the nighttime: it was presumably leading to stronger correlations of UGR with subjective glare ratings under BL conditions. On the other hand, DGP and DGI were developed for daylighting situations in order to evaluate “glare from windows” [45, 148]. This study was conducted in a test room equipped with Anidolic Daylighting Systems; the assessments of “glare from anidolic systems” can be applicable with “glare from windows”. The correlations of subjective and objective glare ratings were sound. DGI was originally based on experiments with “uniform light sources” [144] [279];

it also correlated rather well in this study with the subjective glare ratings issued from a uniform light diffuser such as the textile blinds. Conversely, DGP was developed from a real daylighting situation with windows (representing non-uniform light sources from sunrays), which is less similar to this case: significant correlations of DGP and subjective visual comfort assessments were found, but the correlations were smaller than the correlations with the other two glare indices (DGI and UGR).

For non-visual functions significant correlations were found however, especially for BL conditions (but not for SSL conditions). Higher glare indices were correlated with less alertness, poorer well-being and mood. Interestingly, the non-visual functions had stronger correlations with photometric properties, such as illuminance, CCT, CRI and E_{ec}, than glare indices (see Chapter 5). It seems that the high luminous intensity during bright light conditions was overall perceived as rather uncomfortable and vice versa for the SSL. Further investigations addressing these issues are definitely needed. Correlations of the three glare indices with subjective visual comfort assessments should be investigated hourly and/or with daylight availability in order to better understand the real cause of discomfort glare.

6.3 Conclusion

A favourable objective visual comfort assessment might not always go along with subjective glare ratings in the case of individually controlled lighting systems. It is possible that lighting preference might be able to cancel or reduce visual discomfort, similar to the outside view reported before [49, 50]. A new finding from this thesis is that the glare indices have also significant correlations with non-visual functions, even though these associations not always went in the same directions and were depending on the time of day. Interestingly, they were not well reflected by the absolute values of glare indices.

Taken together, several glare indices, developed for evaluation of discomfort glare, corresponded with subjective assessments of visual comfort. It is believed that this is the right way to develop tools for the assessment of discomfort glare. At present it is not yet very well understood how an appropriate glare index should be chosen to evaluate a given lighting situation (for different populations and environments). Evaluations of discomfort glare are complex, since they deal with subjective sensations; for sure, the surroundings and environment such as view, pleasantness, time of day, daylight availability, etc. play an important role in this prospect. Further investigations are needed; photometric light properties, such as colour appearance and/or circadian metrics must be taken into account, since correlations between these properties and subjective visual comfort assessments were found.

Chapter 7 Conclusion

7.1. Statements and research questions

This doctoral thesis aimed at investigating the impact of light on visual comfort, including both visual and non-image forming (NIF) effects. Two relevant questions were addressed in this work, as mentioned in Section 2.3: i) how can the luminous distribution of environmental lighting be assessed more efficiently inside of buildings? ii) what is the impact of light on human visual comfort including visual and Non-Image Forming (NIF) effects? In this conclusive section, it is shown that the thesis results provided sound answers to both questions.

7.1.1 Valuation of a Camera-Like Light Sensor

A Camera-Like Light Sensor (CLLS) has been introduced in the course of this thesis to foster the use of High Dynamic Range (HDR) imaging techniques for luminance mapping and glare risks assessment in a working space. The CLLS was calibrated for spectral sensitivity, photometric response and corrected for vignetting effects. Implementation of this novel device in real settings can markedly reduce the time for image capturing when compared to HDR image acquisition: it can capture a scene within a single snapshot or record it in real time. Luminance mapping and glare risk assessments were carried out using the CLLS. The results were compared to measurements issued from conventional, but definitively slower, HDR imaging techniques.

In a next step, the CLLS was calibrated for photometric assessments in circadian metrics. A different spectral sensitivity was applied for that purpose by appropriate colored filters. As a result, the circadian weighted radiance could be monitored. The CLLS was also validated for assessments of luminous properties with respect to NIF functions within a realistic office room equipped with Anidolic Daylighting Systems in the LESO experimental building at EPFL. Furthermore, it was used for comparisons of luminance distribution and circadian weighted radiance (Lec) distribution between two test rooms, equipped with different daylighting systems, at the "Berkeley Lab Advanced Windows Testbed Facility" at the Lawrence Berkeley National Laboratory (LBNL, CA, USA).

Finally, the practical implementation of the CLLS was successfully validated in realistic office lighting conditions for both photometric and circadian sensitivity functions. It was efficiently used as a tool to assess luminance distributions within an experimental study with human subjects, as presented below.

7.1.2 Impact of office lighting on visual comfort including Non-Image Forming (NIF) effects

In the course of this thesis, two experiments with young participants were conducted, aiming at testing the acute effects of different lighting conditions on subjective variables in a realistic office room. Subjective assessments, such as visual comfort variables, alertness, mood and well-being were assessed by the participants every 30 and 60 minutes, respectively. Photometric variables were continuously monitored. To systematically assess also inter-individual differences on visual and NIF functions, the second study comprised extreme chronotypes (extreme morning and evening types). They served as 'natural' examples for such inter-individual differences due to their very different habitual working hours and presumably different lighting requirements.

Visual comfort variables

The results from the studies confirmed that office lighting conditions with an intensive use of daylight led to a better visual comfort and were preferred by the subjects when compared to pure electric lighting conditions, although any outside view for the subjects was prevented. It was also confirmed that subjective glare ratings were higher (more intolerable) under electric lighting than under daylight, regardless of outside view, although the vertical illuminance was higher under daylighting conditions.

Under the bright light conditions, where the vertical illuminance was maintained constant at 1000 lx (thanks to complementary electric lighting), visual comfort decreased in the course of the day, as well as light preference. Different sky conditions also influenced the visual comfort variables, such as glare sensations. Higher subjective glare ratings were found at certain times under overcast sky conditions when compared to intermediate and clear skies. Potential effects of light on inter-individual differences of visual comfort and NIF were also identified in different chronotypes. Extreme morning types assessed lower visual comfort and light preference at the beginning of the day than extreme evening type subjects, when they were exposed to constant bright light. This is an interesting finding, because bright morning light can advance the circadian phase to an earlier time. Since morning types have already very early wake- and bedtimes, very bright light in the morning would reinforce this advance. When they could self-select their lighting, extreme morning types chose a lower luminous intensity in the morning which might be an intuitively countermeasure by them to prevent a more advanced timing.

In the study session where the subjects could have their own controlled lighting systems, they predominantly chose daylight, if available, as the preferred light source. The visual comfort and light preference appraisals were very positive; moreover, their assessments did not vary over time. Different sky conditions did not alter the visual comfort appraisal under these lighting conditions. Overall, positive correlations between the photometric properties and the visual comfort variables were found: larger vertical illuminance, correlated colour temperature (CCT), colour rendering index (CRI), and circadian weighted radiance (Eec) correlated with greater light preference, visual comfort and lower subjective glare ratings.

Non-visual functions

The studies outlined the impact of realistic office lighting conditions on subjective NIF effects, such as alertness, mood and well-being. The subjects became definitively sleepier and indicated poorer physical well-being earlier under pure electrical lighting than under daylighting. Under self-selected lighting conditions, varying sky conditions differently affected non-visual functions, such as alertness and mood. An overcast sky led to sleepier subjects than intermediate and clear skies. The subjects were also in a better mood under clear skies later in the evening, when compared to intermediate sky conditions.

The photometric variables had also a significant impact on non-visual functions; larger vertical illuminance, CCT, CRI and E_{ec} correlated with more relaxation, better well-being and a better mood as well as greater alertness under both bright light and self-selected lighting conditions.

Associations between visual and non-visual functions

Strong correlations between visual comfort and light preference were found; visual comfort variables also showed correlations with subjective glare ratings. Moreover, the latter showed slight but significant correlations with non-visual functions: higher subjective glare ratings were correlated with less relaxation and worse mood as well as with worse physical well-being. Greater visual comfort and light preference correlated with a more relaxed attitude, higher alertness, better physical well-being and a better mood. For non-visual functions, strong correlations were found between more relaxation and better physical well-being; both were also correlated with a better mood and higher alertness.

7.1.3 Impact of luminous distribution on visual and non-visual functions

The CLLS was applied to assess the impact of luminous distribution on subjective assessments. Glare indices and background luminances were used to determine the luminous distribution of a scene. Luminance mappings issued from a conventional CCD camera and HDR imaging techniques were employed in the first study; the second used luminance mappings achieved by the CLLS. Sequences of images were recorded over time for both studies; the impact of the luminous distribution on visual and NIF effects were investigated.

Significant correlations between subjective and objective glare assessments were found, especially under bright light conditions. However, it must be outlined that under realistic office lighting, negative objective glare ratings (larger glare indices) do not always lead to poor visual comfort subjective assessments. Preferred lighting conditions, according to the subjects' choice, may prevent against intolerable glare ratings, even if the objective assessments do not differ.

Whether light preference bias and/or the spectrum of light influenced the subjective visual comfort assessments, could not be determined in this study.

A novel finding from this thesis is the association between luminous distributions and non-visual functions, such that high objective glare ratings were associated with less relaxation, poor physical well-being and mood, as well as lower alertness. Preferred lighting conditions seemed to mitigate the negative appraisals of these non-visual functions, as was shown in extreme chronotypes.

It remains necessary to further investigate the variations of discomfort glare over time to integrate results from both objective glare ratings and subjective assessments. Both variables varied during the day due to daylight fluctuations as well as the circadian modulations of our internal clock. To determine optimal lighting conditions, the modulations of environmental factors and internal physiological states need to be considered accordingly.

Novel findings regarding visual comfort

In the two studies, subjective visual comfort assessments showed very high correlations with light preference; they had a similar time course and decreased during the day. A moderate correlation between visual comfort and subjective glare ratings was also found. Visual comfort assessments showed also slight but significant correlations with colour appearance and brightness perception of light, as well as glare indexes (DGP, DGI and UGR). This was also true for non-visual functions such as alertness, well-being and mood: correlations between those visual comfort variables and non-visual functions were found.

To conclude this means that a positive appraisal of visual comfort does not always imply an absence of discomfort glare, as commonly defined. Apart from the absence of luminous sources leading to discomfort glare, lighting preference as well the other visual comfort variables, including non-visual functions, are also involved in the subjective assessment of visual comfort for given lighting conditions.

7.2. Recommendations for office lighting

The intensive use of daylighting within buildings can be promoted as a preferable light source in office rooms, not only for energy saving purposes, but also for the sake of visual comfort and non-visual functions. According to the studies carried out in this thesis, light affects both visual and non-visual functions under realistic lighting conditions

Office rooms with daylight input provide better visual comfort, light preference and less subjective glare. These office lighting conditions can also prevent sleepiness and discomfort glare in the course of the afternoon. Moreover, individually controlled lighting systems play an important role regarding subjective assessments of visual comfort by users. The individual choice of lighting scenarios does not only provide a preferred lighting environment and better visual comfort conditions, it also reduces negative (subjective) assessments of discomfort glare.

7.3. Future outlook

This thesis pointed out some additional open questions. Further research is required to investigate and provide knowledge about the following.

Assessment of daylighting and electric lighting systems in circadian metrics

For the first time, a successful implementation of the CLLS for circadian weighted radiance mapping of advanced daylighting systems was achieved in this thesis. It showed that different daylighting systems provide different luminous distributions at different times of day due to different daylight input fluxes. Interestingly, the different daylight incidence angles did not only provide different illuminance levels, but also modified the spectral composition of daylight. It would be interesting to assess further the circadian weighted radiance maps of other lighting systems - combining daylighting and electrical lighting systems - at different times of day in order to assess the different effects of light with respect to non-visual functions.

Use of CLLS for circadian metrics assessment of visual comfort and non-visual functions

Photometric properties, such as the colour appearance (CCT and CRI) were correlated with subjective assessments of visual comfort. This might therefore be a parameter of visual comfort, like the glare index, which can be analysed in combination with luminous distributions. Based on the findings from the second study, circadian weighted irradiance (Eec) showed correlations with several visual comfort variables under various lighting conditions. Since the CLLS was successfully calibrated and validated in circadian metrics, it would be interesting to implement it in a study involving a comparison with subjective assessments.

Further objective assessments of non-visual functions and cognitive performance

According to this thesis, impacts of light were found on non-visual functions, such as alertness, mood and well-being. Besides these subjective assessments, interesting objective assessments of non-visual functions were also monitored, such as the hormonal onset of melatonin secretion and cortisol salivary concentrations as well as other physiological variables that are currently being analysed. Moreover, performances of visual and cognitive tasks must also be considered to investigate the effects of light. This might further explain the luminous impacts on visual and non-visual functions and may allow an improvement of task performance related variables in a realistic working environment.

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Appendix A

I. Questionnaires for Experiment I.

a) Visual comfort variables

Subject Code :Liper_XX_XX XX.XX.20XX

Echelle de confort visuel

Voici quelques questions concernant l'environnement lumineux de cette salle. Veuillez marquer votre consentement avec chaque déclaration sur la ligne correspondante.

(1) J'aime la lumière dans cette salle.

OUI ———————————————— **NON**

(2) Globalement, l'éclairage de cette salle est agréable.

OUI ———————————————— **NON**

(3) Cette salle me semble trop lumineuse.

OUI ———————————————— **NON**

(4) Cette salle me semble trop sombre.

OUI ———————————————— **NON**

(5) Il n'y a pas assez de lumière pour travailler / lire correctement.

OUI ———————————————— **NON**

(6) Il y a trop de lumière pour travailler / lire correctement.

OUI ———————————————— **NON**

(7) Comment ressentez-vous l'éblouissement dans cette salle.

Juste Perceptible **Juste acceptable** **Juste inconfortable** **Juste intolérable**

Imperceptible **Perceptible** **Acceptable** **Inconfortable** **Intolérable**

b) Non-Image Forming (NIF) functions

Subject Code : Liper_XX_XX XX.XX.20XX

Indiquez sur l'échelle suivante avec un trait, comment vous vous sentez <u>en ce moment.</u>

Extrêmement relaxé	____________________	Extrêmement tendu
Physiquement à l'aise	____________________	Physiquement pas du tout à l'aise
Extrêmement éveillé	____________________	Extrêmement fatigué
Rassasié	____________________	Affamé
De mauvaise humeur	____________________	De très bonne humeur
Extrêmement froid	____________________	Extrêmement chaud

Remarques :

Test Number: 1

II. Questionnaires for Experiment II.

a) Visual comfort variables

Subject Code : Chroli_xx_xx XX.XX.20XX

Echelle de confort visuel (part 1)

Voici quelques questions concernant l'environnement lumineux de cette salle. Veuillez marquer votre consentement avec chaque déclaration sur la ligne correspondante.

(1) J'aime la lumière dans cette salle.

OUI ——————————————— **NON**

(2) Globalement, l'éclairage de cette salle est confortable.

OUI ——————————————— **NON**

(3) Il n'y a pas assez de lumière pour travailler / lire correctement.

OUI ——————————————— **NON**

(4) Il y a trop de lumière pour travailler / lire correctement.

OUI ——————————————— **NON**

(5) La lumière est mal distribuée dans cette salle.

OUI ——————————————— **NON**

(6) Comment ressentez-vous l'éblouissement dans cette salle.

Juste Perceptible | **Juste acceptable** | **Juste inconfortable** | **Juste intolérable**

———————————————

Imperceptible | **Perceptible** | **Acceptable** | **Inconfortable** | **Intolérable**

Test Number: 1

Subject Code : Chroli_XX_XX XX. XX. 20XX

Echelle de confort visuel (part 2)

Voici quelques questions concernant l'environnement lumineux de cette salle. Veuillez marquer votre consentement avec chaque déclaration sur la ligne correspondante.

(7) La couleur de ma peau apparait peu naturelle sous cet éclairage.

OUI ———————————————— **NON**

(8) La lumière dans cette salle est trop « chaude » pour un lieu de travail.

OUI ———————————————— **NON**

(9) La lumière dans cette salle est trop « froide » pour un lieu de travail.

OUI ———————————————— **NON**

(10) Si je compare la situation lumineuse de cette salle avec d'autres dans lesquels j'ai travaillé auparavant, je dirais que la situation lumineuse ici est ...

meilleure

plutôt meilleure

plutôt pareille

plutôt pire

pire

(11) Dans le cadre d'une journée de travail, je pourrais bien m'imaginer travailler dans cet environnement lumineux pendant …

moins de 2 heures

2 à 4 heures

4 à 6

plus que 6 heures

b) Non-Image Forming (NIF) functions

CHROLI_XX__XX	XX.XX.20XX

Indiquez sur l'échelle suivante avec un trait, comment vous vous sentez <u>en ce moment.</u>

Extrêmement relaxé ______________________ Extrêmement tendu

Physiquement à l'aise ______________________ Physiquement pas du tout à l'aise

Extrêmement éveillé ______________________ Extrêmement fatigué

Rassasié ______________________ Affamé

De mauvaise humeur ______________________ De très bonne humeur

Extrêmement froid ______________________ Extrêmement chaud

Remarques :

Test Number: 1

Curriculum Vitae

Contact information : apiparn@gmail.com

Employment history

2009-Present	Research & Teaching Assistant	Solar Energy and Building Physics Laboratory Ecole Polytechnique Fédérale de Lausanne (EPFL)
2009	Visiting Scholar	Solar Energy Research Institute of Singapore National University of Singapore
2007 – 2008	Research Assistant	Solar Energy and Building Physics Laboratory Ecole Polytechnique Fédérale de Lausanne (EPFL)
2003-2007	Project Lighting Designer	Vision Design Studio in Bangkok, Thailand
2003	Intern Lighting Designer	Light Cibles & Louis Clair in Paris, France
1999 – 2001	Architect	Terra Architect in Bangkok, Thailand

Education

2009-Present	PhD	Doctoral Program in Environment (EDEN) Ecole Polytechnique Fédérale de Lausanne (EPFL)
2003-2003	Graduate School Master of Applied Arts	DESS Art Appliqués: Colour in environment projects (Mention Bien) Université de Toulouse II Le Mirail
1994-1999	University	Factulty of Architecture, Chulalongkorn University

Professional qualifications

Certification	Diplôme d'études en langue française, 1er degré	
	Université Stendhal – Grenoble III, France	
Accreditation	License no. Arch. 5527 (Thailand)	
Computer Skills	General	Auto CAD, Adobe Photoshop /Illustrator, MS Office
	Specific	Evalglare, Radiance, Dialux, Relux, Photosphere, LESOSAI
Languages	Thai	Mother Tongue
	English	Fluent (Module C1)
	French	Fluent (Module B2)

Awards

2012	PhD Mobility Awards	Doctoral Program in Civil and Environmental Engineering
		Ecole Polytechnique Fédérale de Lausanne (EPFL)
2013	Winner of Science Slam	Thai Student Academic Conference, Göttingen, Germany

Publications

Articles in peer reviewed journals

Münch M, Linhart F, Borisuit A, Jaeggi SM, Scartezzini JL. Effects of prior light exposure on cognitive performance, subjective sleepiness, and hormonal secretion in the evening. *Behavioral Neuroscience*, 2012, 126 (1):196-203. Epub 2011 Dec 26.

Borisuit A, Scartezzini J-L, Thanachareonkit A. Visual Discomfort and Glare Rating Assessment of Integrated Daylighting and Electric Lighting Systems using HDR Imaging Technique. *Architectural Science Review*, 53 (4), 359-373

Peer reviewed conference proceedings

Borisuit A, Deschamps L, Kämpf J, Scartezzini J-L, Münch M. Assessment of circadian weighted radiance distribution using a camera-like light sensor. Proceedings of *CISBAT2013 International Scientific Conference*; Lausanne, Switzerland, September 4-6, 2013.

Borisuit A, Münch M, Deschamps, L, Kämpf J, Scartezzini J-L. A new device for dynamic luminance mapping and glare risk assessment in buildings. Proceedings of *SPIE2012 International Symposium on Optical Engineering*; San Diego, USA, August 13-16, 2012.

Borisuit A, Linhart F., Kämpf J, Scartezzini J-L , Münch M. Comparison of objective and subjective visual comfort and associations with non-visual functions in young subjects. Proceedings of *CISBAT2011 International Scientific Conference*; 2011 Lausanne, Switzerland, September 14-16, 2013.

Basurto C, Borisuit A., Kämpf J, Münch M., Scartezzini J-L. Daylight Optimization of buildings and application of advanced daylighting systems in central Mexico. Proceedings of *CISBAT2011 International Scientific Conferenc*e; Lausanne, Switzerland, September 14-16, 2013.

Professional membership

Member of Association of Siamese Architects under the Royal Patronage (ASA), Thailand

Others

2011-2012 President of the Association of Thai Students in Switzerland (ATSS)